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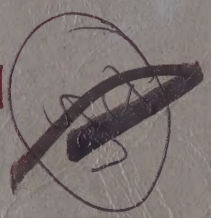
INSTRUCTIONS

For The

ENGEN MICROWAVE WATTMETER SYSTEM

WESTON MODEL 1493-1 BOLOMETER BRIDGE



WESTON MODEL 1494-1 REFERENCE CURRENT GENERATOR

STANDARDS LABORATORY

THE WORLD LEADER IN WESTON MEASUREMENT AND CONTROL

MP MASTER
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DAYSTROM, INCORPORATED, WESTON INSTRUMENTS DIVISION
Newark 14, New Jersey, U. S. A.

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INSTRUCTIONS

For The

ENGEN MICROWAVE WATTMETER SYSTEM

WESTON MODEL 1493-1
BOLOMETER BRIDGE

WESTON MODEL 1494-1
REFERENCE CURRENT GENERATOR

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Newark 14, New Jersey, U. S. A.

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TABLE OF SPECIFICATIONS

Model 1493-1 Bolometer Bridge -

Accuracy:	0.1% of retracted d-c power plus 0.1 microwatt with external current-measuring means of high accuracy.
Range:	Nominally 100 microwatts to 35 milliwatts with full accuracy.
Bolometers:	External barretters or thermistors. Bias range: 1.5 to 15 ma. Resistance: 50, 100, or 200 ohms with internal standard; other values with external standard.
Standard Resistors:	Two 100-ohm resistors sealed in oil, certified to 0.01%; connections for 50, 100, or 200 ohms on front of panel.
Power Requirements:	117 v, 50-60 cps, 65 watts.
Panel:	8.75" x 19", for rack mounting.
Weight:	30 pounds without case; 55 pounds with case.

Model 1494-1 Reference Current Generator -

Output:	3 to 30 ma, adjustable within 0.01 microampere.
Stability:	10 parts per million in a 15 minute period after warmup.
Power Requirements:	117 v, 50-60 cps, 60 watts.
Panel:	8.75" x 19", for rack mounting.
Weight:	25 pounds without case; 55 pounds with case.

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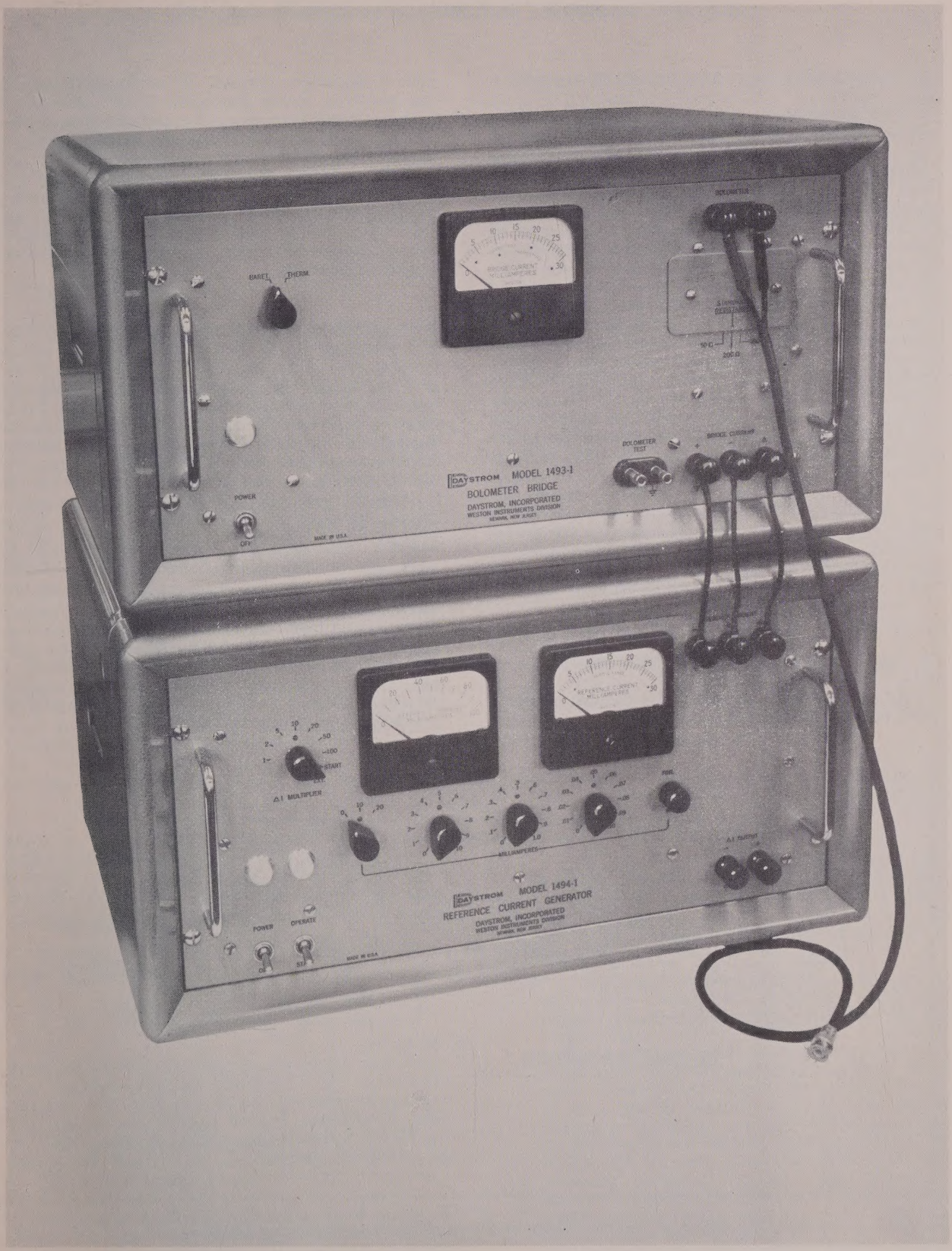


Figure 1. Bolometer Bridge and Reference Current Generator.

SECTION I GENERAL DESCRIPTION

1. ENGEN MICROWAVE WATTMETER SYSTEM

The Engen system for the measurement of microwave power is essentially an automatic direct-current bolometer bridge in which the bolometer resistance is maintained precisely at a fixed value against a certified standard resistance by means of a d-c feedback system. When r-f power is applied to the bolometer, the feedback system reduces the d-c component of bolometer current to maintain the total bolometer resistance at a constant level. The reduction of d-c bolometer power is proportional to the applied r-f power and is measurable to an accuracy of 0.1% when the unit is in combination with highly accurate direct-current measuring instruments (see Figure 2). A d-c amplifier receives error current from the normally balanced terminals of a Wheatstone bolometric bridge. This drives a power amplifier which delivers the current required to balance the bridge. A reversing switch between the amplifiers maintains a negative feedback with bolometers of both positive and negative temperature coefficient.

In effect, the Engen system is an automatic a-c/d-c transfer procedure in which the dissipative element, the bolometer, is maintained at a precisely known value of resistance. Glenn F. Engen's detailed discussion of the method is included as an appendix to this manual.

2. DESCRIPTION OF BOLOMETER BRIDGE

The Weston Model 1493-1 self-balancing bolometer bridge (see Figure 1, upper unit) is the basic unit of the Engen system. It automatically adjusts the d-c bias power dissipated in the bolometer to maintain the bolometer's d-c resistance at a constant level. The bridge comprises the resistances (which form a bridge circuit when connected to a bolometer), and d-c amplifier of exceptional gain, zero stability and phase response. These components are connected in a feedback circuit so that the bridge unbalance signal is amplified to produce bridge current which will tend to balance the bridge. A regulated plate voltage supply is included.

3. DESCRIPTION OF REFERENCE CURRENT GENERATOR

The Model 1494-1 Reference Current Generator is an accessory to the Model 1493-1 Bolometer Bridge and provides an adjustable and highly stable current to facilitate the accurate measurement of difference between two currents from the bolometer bridge. The use of a constant-current auxiliary source for this purpose is described in a discussion by Engen, a reprint of which is included as an appendix to this manual. This generator delivers an adjustable direct current to an external circuit, the magnitude of the current remaining substantially unchanged with changes in potential across the load between 0 and 30 volts. It comprises a mercury cell for reference potential, an adjustable mutual shunt resistor, and a d-c amplifier with regulated power supply similar to the one in the bolometer bridge. Current output is adjustable from 3 to 30 ma, with an incremental adjustability of 0.01 microampere.

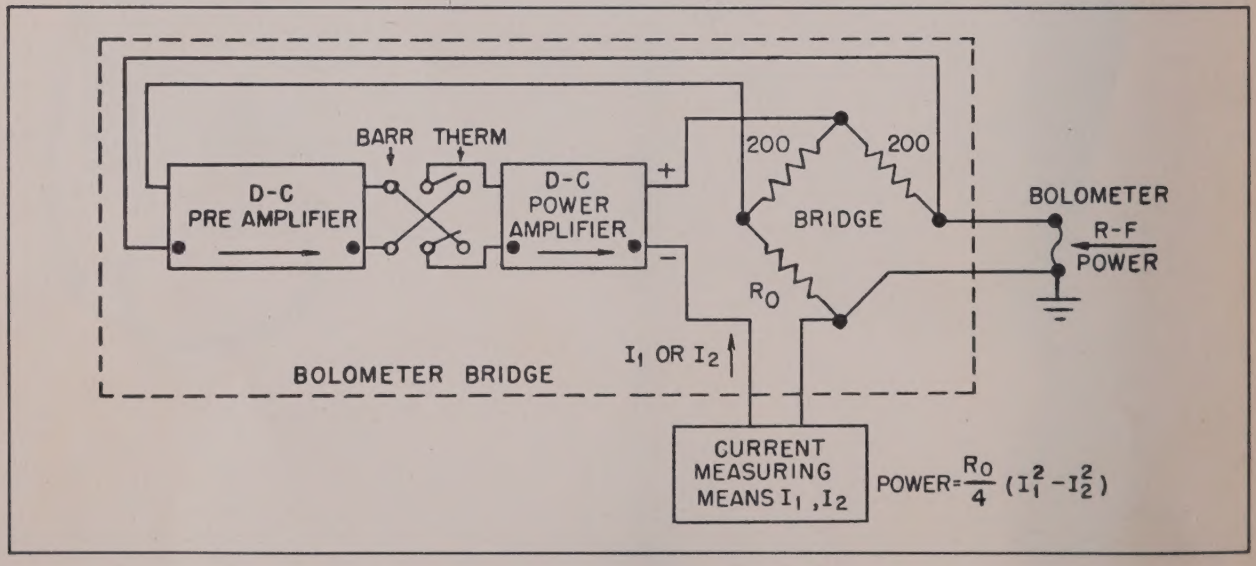


Figure 2. Basic Circuit of Engen Microwave Wattmeter System

SECTION II DESCRIPTION AND OPERATING PRINCIPLES

1. GENERAL

The Engen Microwave Wattmeter System has been thoroughly tested and inspected before being shipped. It is important for the operator to familiarize himself with the equipment by performing a preliminary test, as in Paragraph 3, Section III, before performing the high accuracy measurements for which the equipment is designed.

2. SYSTEM OPERATION

A panel switch on the Bolometer Bridge, permits the instrument to operate with either a barretter or a thermistor bolometer. The bridge current range is 3 to 30 ma which corresponds to a bolometer bias range of 1.5 to 15 ma. Bridge current is delivered to external current-measuring instruments through binding posts on the instrument panel. The current is monitored by means of a panel milliammeter rated at 2% accuracy. The panel meters provide a convenient method of monitoring current. However, to achieve the highest accuracy for the bolometer bridge, bridge current must be carefully measured with external current measuring instruments.

With the bridge energized and a bolometer connected, bridge current automatically rises to the level where the bolometer resistance is equal to the standard resistance of 50, 100 or 200 ohms in the bridge. When r-f power is added to d-c power in the bolometer, the bridge current automatically falls from its initial value of I_1 to a lower value of I_2. This is necessary in order to maintain a constant bolometer resistance. The d-c power change in the bolometer is

$$P = \frac{R_0}{4}(I_1^2 - I_2^2) \qquad (1)$$

where R_0 is the ohmic resistance of the bolometer, I_1 and I_2 are the bridge currents in milliamperes and P is the power change in microwatts (retracted d-c power). Appropriate correction factors should be applied to calculate r-f power (see Section II-3. B.).

In theory, the maximum power which can be measured with a given bolometer is

$$P = \frac{1}{4} R_0 \ I_1^2 \qquad (2)$$

which corresponds to replacing the entire component of d-c bias power with r-f power ($I_2 = o$). In practice, however, the value of I_2 is not allowed to drop below 1/2 or possibly 1/3 of I_1. This is necessary in order to retain satisfactory self-balancing and highest accuracy and permits the measurement of power over 75-90% of the theoretical range.

For power measurements in excess of a nominal 40% of the theoretical limit, bridge currents I_1 and I_2 are measured individually to an accuracy of 0.03% by means of a potentiometer and external shunts. The retracted d-c power is determined to an accuracy of 0.1% plus 0.1 microwatt. The useful measuring range for a typical 200 ohm barretter requiring 8.5 ma of bias current will be 5.8 to 13 mw (milliwatts). With a 200 ohm bolometer requiring the maximum bias the instrument can deliver (15 ma), the range will be approximately 18 to 40 mw.

To maintain this accuracy for smaller powers, $I_1 - I_2$ is measured directly by means of a differential technique. The Weston Model 1494-1 reference current generator is used for this purpose (see Figure 1, lower unit). This enables the bolometer bridge to measure power in the microwatt range. The generator delivers an adjustable direct current with very high short-time stability. Current output is connected differentially to the output of the bolometer supply circuit (see Figure 3). The current output is adjusted to balance bridge current I_1 before r-f power is applied to the bolometer. When r-f power is applied, the bridge current is reduced automatically to I_2 (to maintain bridge balance) and the reference current remains constant at I_1. Even when relatively small, the difference between the two currents, ΔI, can be measured with high accuracy. The retracted d-c power can be computed from:

$$P = \frac{R_0}{4} (2I_1 - \Delta I) \Delta I \qquad (3)$$

where P is the retracted d-c power in microwatts, R_0 is the ohmic resistance of the bolometer, I_1 is the current from the reference current generator and ΔI is the difference between generator current I_1 and bridge current I_2, all in milliamperes. Appropriate correction factors should be applied to calculate r-f power (see Section II-3. B.).

3. BOLOMETER BRIDGE

A. Operating Principles

The basic circuit for the Model 1493-1 Bolometer Bridge is shown in Figure 4. The bolometer, located in a suitable coaxial or waveguide mount, is connected to a symmetrical resistance bridge for balance against a precision 200, 100 or 50 ohm resistor.

The bridge null terminals are connected to a high-gain d-c amplifier. The amplifier drives a triode-connected power tube which controls the bridge-supply current. This forms a feedback loop about the bridge which is degenerative with respect to the volt-ampere characteristic of the power-sensitive bolometer. The bridge is thereby balanced by feedback control of the bridge current to the point where the bolometer resistance is equal to the standard reference resistance. With a cold barretter (positive temperature coefficient), terminal 1 of the bridge will be negative with respect to terminal 2. These polarities will be reversed with a cold thermistor (negative t. c.). When the reversing switch is correctly set, a rising temperature in either kind of bolometer produces a negative-going voltage change at the grid of the power tube.

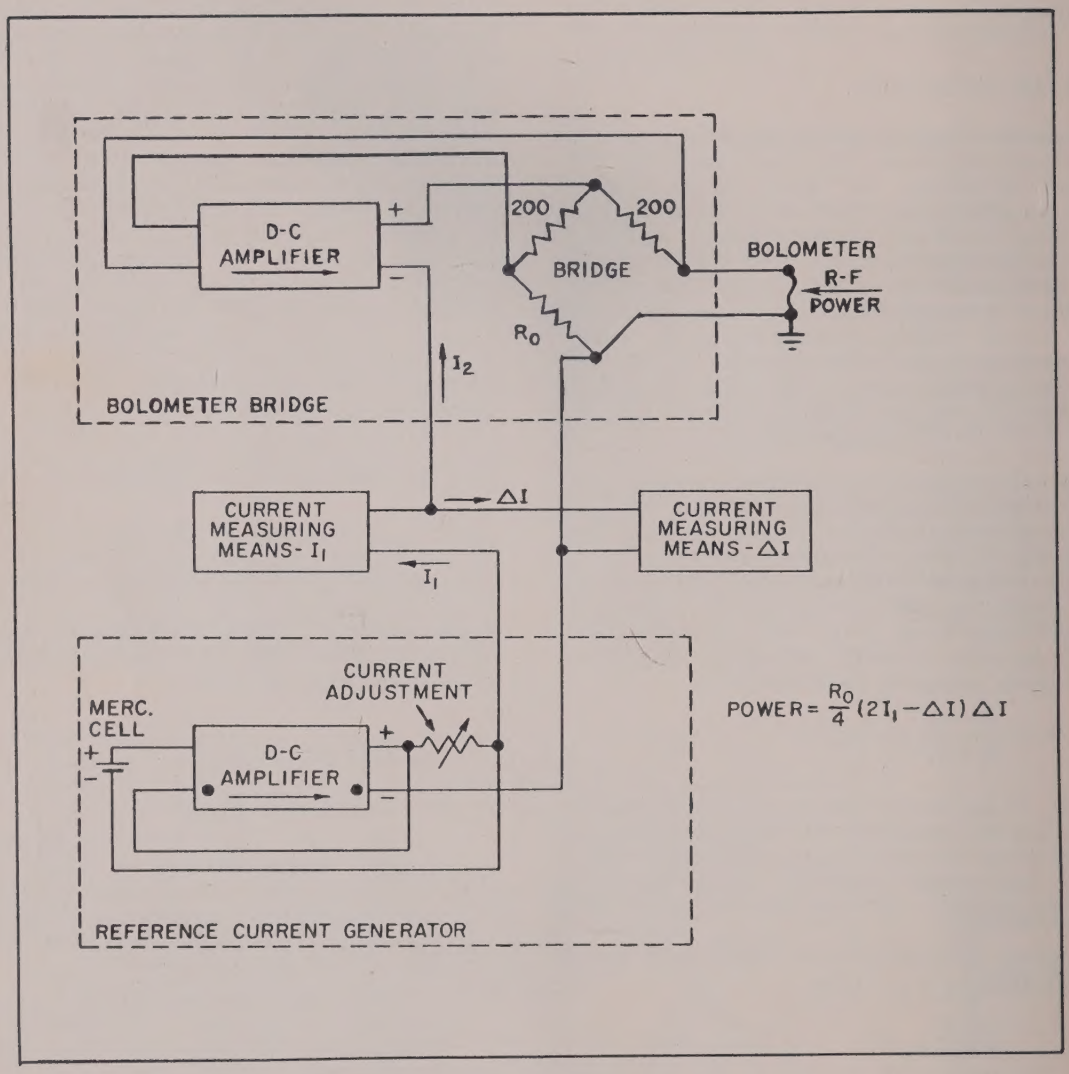


Figure 3. Connection of Bolometer bridge and reference current generator for low-power measurement.

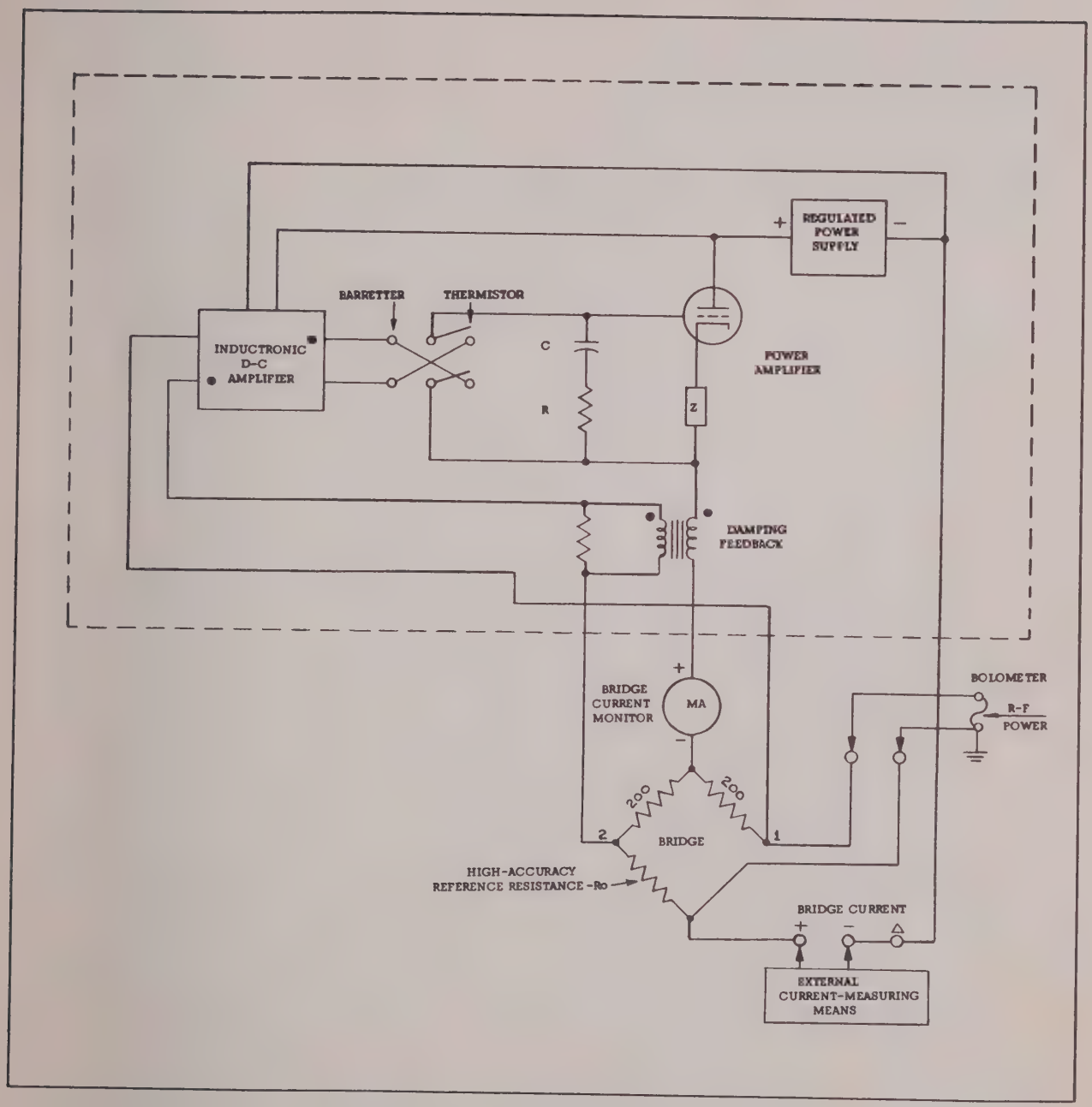


Figure 4. Basic Circuit of Bolometer Bridge

The high feedback-loop gain around the thermally-delayed bolometer requires the inclusion of a derivative feedback for damping. The R-C circuit shown across the output of the d-c amplifier, and the damping feedback inductor, provide enough damping to maintain stability with an ordinary barretter or thermistor.

B. R-F Power Calculation Correction Factors

Equation 1 is the fundamental equation for bolometric power. Equation 3 and the equations given in Figures 12 and 13 are directly derived from it. In practice, two correction factors must be applied to any of these equations to calculate r-f power. These factors are described below. Taking these factors into consideration, the equation for r-f power becomes

$$P_{rf} = \frac{R_0}{4K} (I_1^2 - I_2^2) (1 - \frac{R_1}{R_0}) \qquad (4)$$

(1) Lead Resistance

The connecting lead between the bolometer and the bridge carries d-c current bias only. To ensure against possible errors caused by lead resistances, the connections are made through forked lugs and binding posts. The lead resistance is so low (0.036 ohms) as to be ordinarily negligible.

The correction factor for lead resistance is: $1 - R_1/R_0$ where R_1 is the lead resistance and R_0 is the bolometer resistance. When using the cable supplied with the bridge, the correction factors for 50, 100 and 200 ohm bolometers will be 0.99928, 0.99964, and 0.99982 respectively.

(2) Effective Efficiency (K) of Bolometer Mount

Measured (i.e., substituted d-c) power differs from the r-f power for which it is substituted because of mount inefficiency and substitution error. Mount inefficiency results from r-f losses outside the bolometer resistor and substitution error results from a change of current distribution when r-f is substituted for d-c power in the bolometer. The ratio of d-c substituted power to the r-f power dissipated in the bolometer mount is called the effective efficiency (K). In all cases, the substituted d-c power determined by means of the Bolometer Bridge (with or without the Reference Current Generator) must be divided by the effective efficiency to determine the value of r-f power dissipated within the bolometer mount.

The effective efficiencies of stable bolometer mounts range from 0.94 to 0.99. Bolometer mounts can be calibrated by comparison with a mount of known effective efficiency. This is done by using the Bolometer Bridge and following methods contained in the subject literature*. The National Bureau of Standards at Boulder, Colorado, provides determinations of effective efficiencies for bolometer mounts at several frequencies. These determinations are certified to an absolute accuracy of 1%.

C. Standard Resistance Network

One end of the bolometer is grounded when used with a grounded bolometer mount. The direction of current flow is such that the ungrounded bolometer terminal is at positive potential with respect to the other. The bridge resistance, which is directly connected to the grounded end of the bolometer, is the basic element in the system on which calibration depends. It is made of a wire having a very low temperature coefficient of resistance and a low thermal emf against copper. The wire is divided into two sections of 100 ± 0.01 ohms each. The four ends of the sections are connected to binding posts which can be linked together by movable copper links to put 50, 100, or 200 ohms into the circuit. The two 100-ohm sections and two ratio arms of 200 ± .2 ohms are enclosed in a sealed metal box full of oil. This box can be removed easily from the rest of the apparatus for recertification without disturbing any connection whose resistance would affect accuracy (see Section IV, 3.A.). Figure 5 shows the Standard Resistance Network removed from the Bolometer Bridge.

D. Grounding and Circuit Isolation

The binding posts used to insert a suitable current measuring instrument in the path of the total bridge current are connected so that one end of the measuring instrument also is grounded. This places the instrument between the negative end of the high-voltage plate-current supply and ground. Therefore, the negative end must not be at ground potential as is common practice. The chassis on which the regulated power supply and amplifier are mounted is insulated from the grounded panel and supporting structure. To insure that leakage current from the positive end of the power supply (bypassing the bridge to ground and flowing through the measuring instrument) is reduced to a negligible quantity, insulating materials of the highest quality are used between the chassis and grounded parts. Also, a special isolating transformer is interposed between the power line and the circuitry on the insulated chassis. The resistance between the secondary of this transformer and its primary and ground is several hundred thousand megohms.

*G. F. Engen, "Recent developments in the field of microwave power measurements at the NBS," IRE Trans. on Instrumentation, vol. 1-7, pp. 304-306, December 1958.
R. W. Beatty and A. C. McPherson, "Mismatch errors in microwave power measurements," Proc. IRE, Vol. 41, pp. 1112-1119; September 1953.

Figure 5. Standard Resistance Network

It should be noted that the front panel terminals of the 1493-1 Bolometer Bridge marked ⏚ are at ground potential only in the following cases:

(1) When the 1493-1 Bolometer Bridge is connected to a grounded bolometer mount. The terminals marked ⏚ are then connected to ground through the external bolometer cable.

(2) When a jumper is placed across the 1493-1 Bolometer Bridge rear chassis "CKT GRD" terminals. The terminals marked ⏚ are then connected to ground through the three-wire line cord.

(3) When the 1493-1 Bolometer Bridge is connected to a 1494-1 Reference Current Generator which has a jumper across its rear chassis "CKT GRD" terminals.

E. Thermal Potentials

Thermal and contact potentials in the sensitive circuit are minimized by use of low-thermal-emf copper resistance wire and brass binding posts.

F. Accuracy of Balance

With a typical bolometer, the total contribution to the error in determining bolometric power due to failure of the d-c amplifier to balance the bridge exactly, or deviations of the bridge arms from their nominal value, will not exceed 0.03%.

G. Noise

The total rms noise voltage appearing across the bolometer is less than 2 mv.

4. REFERENCE CURRENT GENERATOR

A. Application to Bolometer Bridge

Figure 6 shows the connections between the reference current generator and the bolometer bridge as well as the essential elements of the internal circuitry most closely associated with the external connections. The reference-current and bridge-current circuits are connected in parallel to a current-measuring instrument so that the reference and bridge currents flow through the instrument in opposite directions. The instrument measures the difference between the currents.

In operation, the reference current output is initially short-circuited by setting a range switch to START. The bolometer bridge is brought into operation without r-f power in the bolometer. The reference current then is adjusted to approximate equality with the bridge current. The short circuit is opened by turning the range switch. The reference current is further adjusted to exact equality as indicated by zero difference current. The r-f power then is applied to the bolometer and difference current appears. The difference current, Δ I, and the reference current, equal to I_1, are measured. Three values are inserted in equation 3 of this section to calculate the substituted d-c power.

B. Operating Principles

In operation, current from the d-c amplifier flows through a current-setting shunt and the load. The difference between the potential drop of the shunt and the emf of the reference cell is supplied to the input of the amplifier. The amplifier automatically adjusts the output current to produce a potential balance. Special precautions have been taken to maintain excellent short-time stability of shunt resistance and cell potential. The most important resistors are made of Evanohm wire, which has a very low temperature coefficient over a wide temperature range. Other resistors are of manganin wire and of metal film. The wire-wound resistors are enclosed in a metal box with a foamed plastic lining. The reference cell is enclosed in a metal box with foam lining. The box is thermally isolated from the equipment by non-metallic spacers. These precautions produce a stability of output current over a 5-minute period better than 1 part in 100,000 after a 1-hour warmup.

C. Reference Cell

The reference cell is a Mallory Mercury A Battery, Mallory Catalog No. RM-42R. The normal voltage is 1.35 volts. In service, practically no current is drawn from the cell. Its lifetime is the same as its shelf life. A time-delay relay under control of the main power switch disconnects the cell at all times when the amplifier is not operative. Further protection is provided from small discharges of electricity which occur with switching transients and cause cell voltage to dip and recover slowly. To prevent this in the course of very high precision measurements, a resistance can be switched into the cell circuit during switching operations. This will limit cell current to 1/2 ma under the worst possible condition. In order to prevent rapid drift of electromotive force, the cell is enclosed in a thermally isolated and lagged enclosure. Replace the reference cell annually regardless of test voltage. Do not substitute any other type of battery since the characteristically stable potential of the mercury battery is necessary.

5. DC AMPLIFIER

A. General

The d-c amplifier used in both units is a Weston Inductronic ® Amplifier, followed by a single triode-connected vacuum tube, which produces a total current gain in excess of 200,000. The amplifier contains an induction galvanometer for converting d-c to a-c at 200 kc for amplification with subsequent rectification. The absence of breaker contacts in the input circuit results in

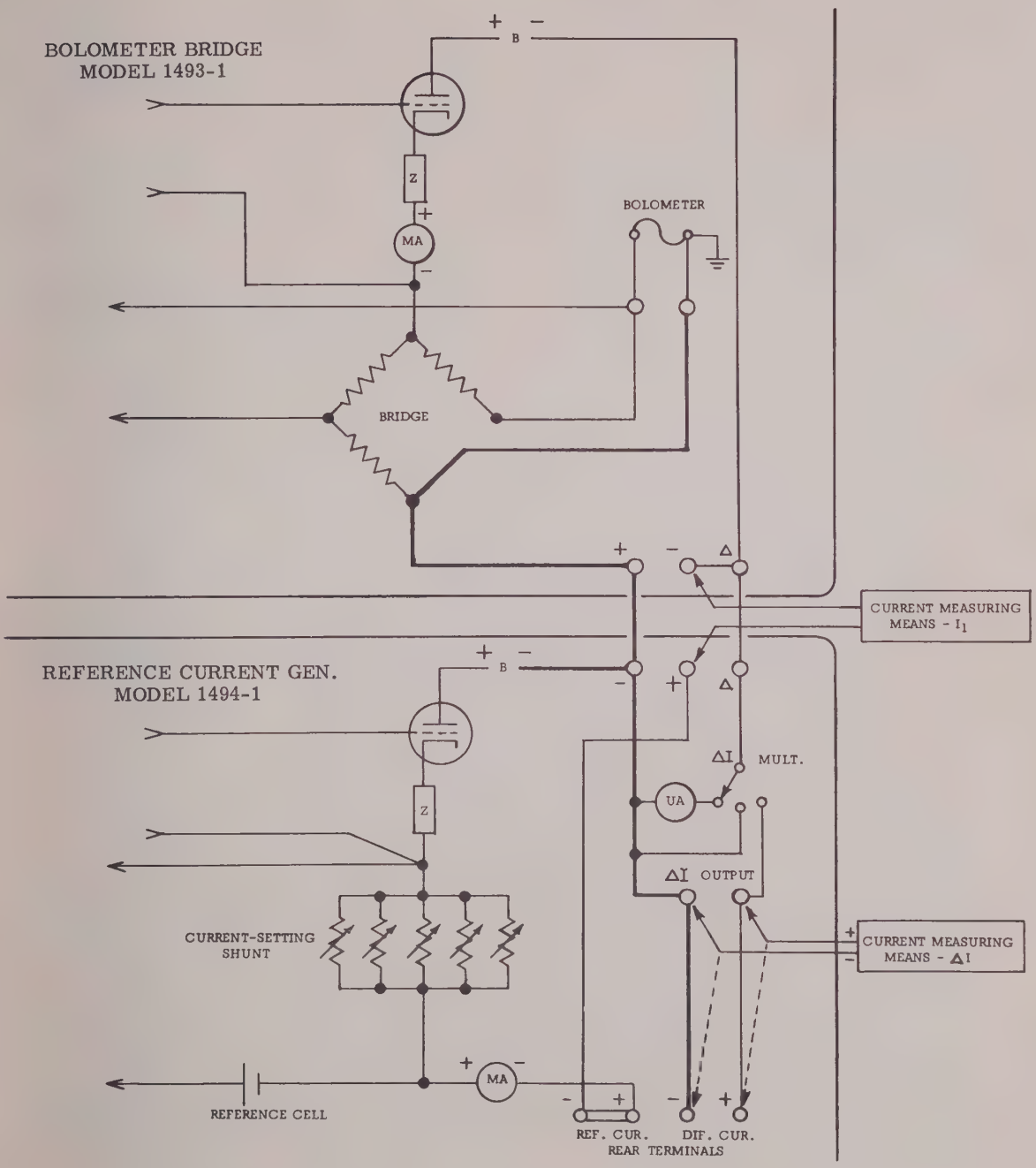


Figure 6. Connection of bolometer bridge and reference current generator.

a noise and drift level below 5 microvolts. The output tube is so biased that any failure in the driving amplifier causing the control voltage in the grid circuit to fall to zero will lower the bridge current to a safe level of about 6 ma. A time-delay relay under control of the main power switch holds down the plate-supply voltage until all cathodes are hot. This prevents bolometer burn-out due to startup transients.

B. Operation

The amplifier basically consists of a moving coil galvanometer which can alter the mutual coupling of an oscillator circuit. This causes frequency changes which are detected in an f-m discriminator and produces a large d-c output from the amplifier. The resolution sensitivity of the amplifier (amount of input signal dissipated in the amplifier) is 5 microvolts.

The following is a technical description of the operation of the amplifier circuit.

The Model 1401 Induction Galvanometer shown in Figure 7 is a permanent-magnet moving coil instrument. It is equipped with an a-c field coil and magnetic structure for injection of high-frequency magnetic flux into the permanent magnetic field. When the moving coil is deflected by direct current from its normal zero center position, it couples proportionately to the a-c field component. This induces an a-c potential in the coil proportional to the direct current. This action derives energy from the field excitation energy and so has a conversion gain rather than the usual percentage efficiency. The energy gain is large, at least 10^9 increase over the d-c input energy. This eliminates the need for further sensitive amplification and simplifies the electronic section considerably. The conversion action delivers an a-c potential in the order of millivolts upon a few seconds of angle deflection of the moving coil, making the system very responsive. The operating frequency of field excitation is 200 kc. The moving coil is pivoted, rather than torsion-suspended, as is usual in sensitive galvanometers.

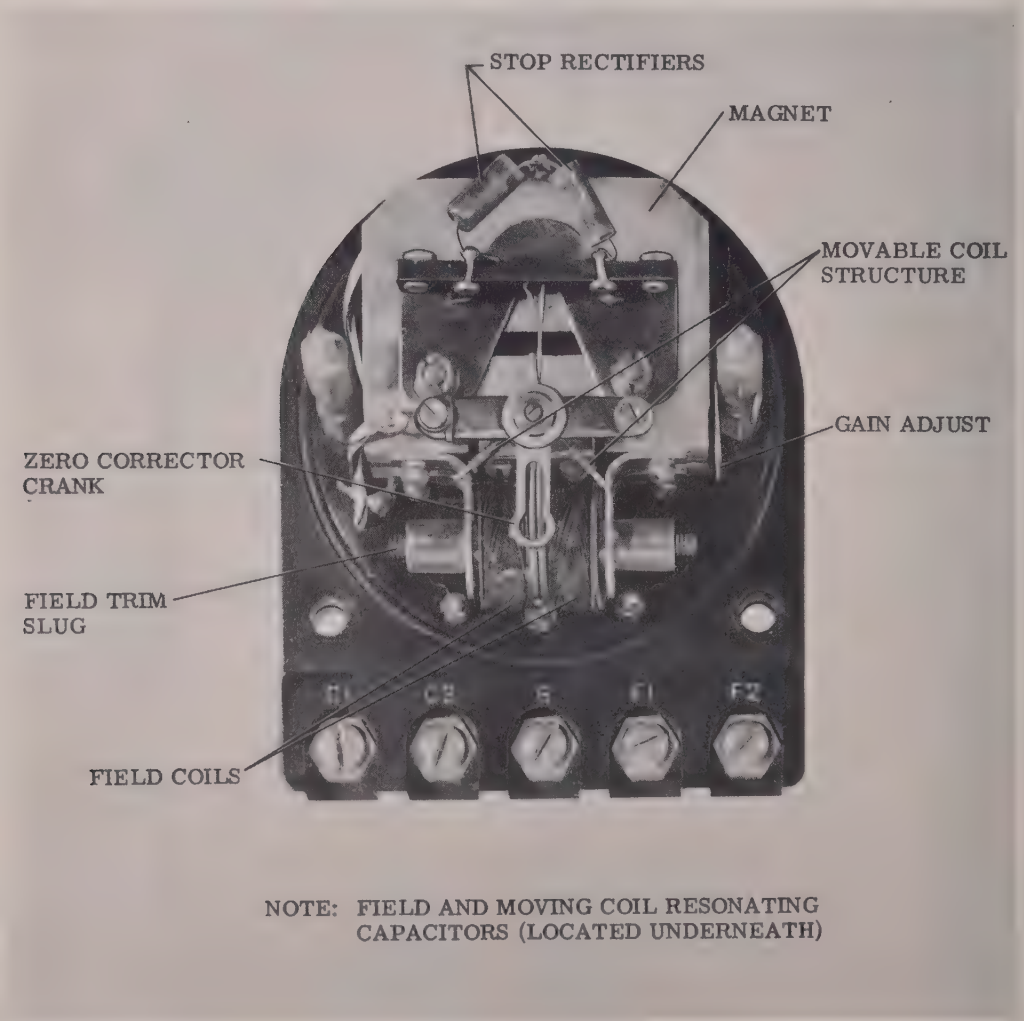


Figure 7. Weston Model 1401 Induction Galvanometer - top view with cover removed.

The galvanometer includes live contacts as mechanical stops to prevent stop adherence. The stops are grounded through diodes which develop rectified d-c to return the moving coil to its center position in the event of stop contact.

The amplifier section consists of a preamplifier stage, V-601A, and two following stages, V-601B and V-602, which are regenerated for oscillation. The galvanometer moving coil circuit is coupled to V-601A by input transformer T-601. V-601A is coupled to V-601B by interstage transformer T-602. The oscillating stages are capacitor-coupled by C-603. The output of the third stage is coupled to discriminating rectifier V-603 by discriminating transformer T-603. All transformers are tuned to the operating frequency of 200 kc.

The Amplifier Section operates as a frequency-shift oscillator rather than as a conventional magnitude amplifier. The last two stages, V-601B and V-602, are regenerated by feedback resistor R-603 for oscillation about the center frequency of 200 kilocycles. The output is applied to the induction galvanometer to excite the field. A-C developed by deflection of the moving coil is applied to V-601A where it is amplified and injected as an additional feedback component into V-601B. Because of the very loose coupling through the galvanometer with small moving coil deflection, this feedback component is essentially in quadrature with the feedback through regenerating resistor R-603. The feedback component has a phase that is a function of the direction of deflection. This causes the frequency of oscillation to deviate from the center frequency of 200 kc in a direction and degree proportional to galvanometer deflection.

Frequency discriminating rectifier V-603 develops the output direct current in response to frequency shift. It is similar in circuit to the balanced phase discriminator commonly used as a detector in frequency-modulated radio receivers.

6. POWER SUPPLY

The d-c power supply for both units is dynamically regulated, primarily to avoid intrusion of line voltage variations and to filter out the residual supply ripple. The actual supply voltage is not critical with the nominal level at 225 volts.

SECTION III CONTROLS AND OPERATING PROCEDURES

1. OPERATING CONTROLS

The purpose of this section is to identify the microwave wattmeter controls and to outline step by step operating procedures for the unit. Figures 8 and 11 are front views of the unit with all controls labeled to aid the operator in becoming familiar with the unit. Figures 10 and 13 list and describe the functions of the various front panel and rear chassis controls.

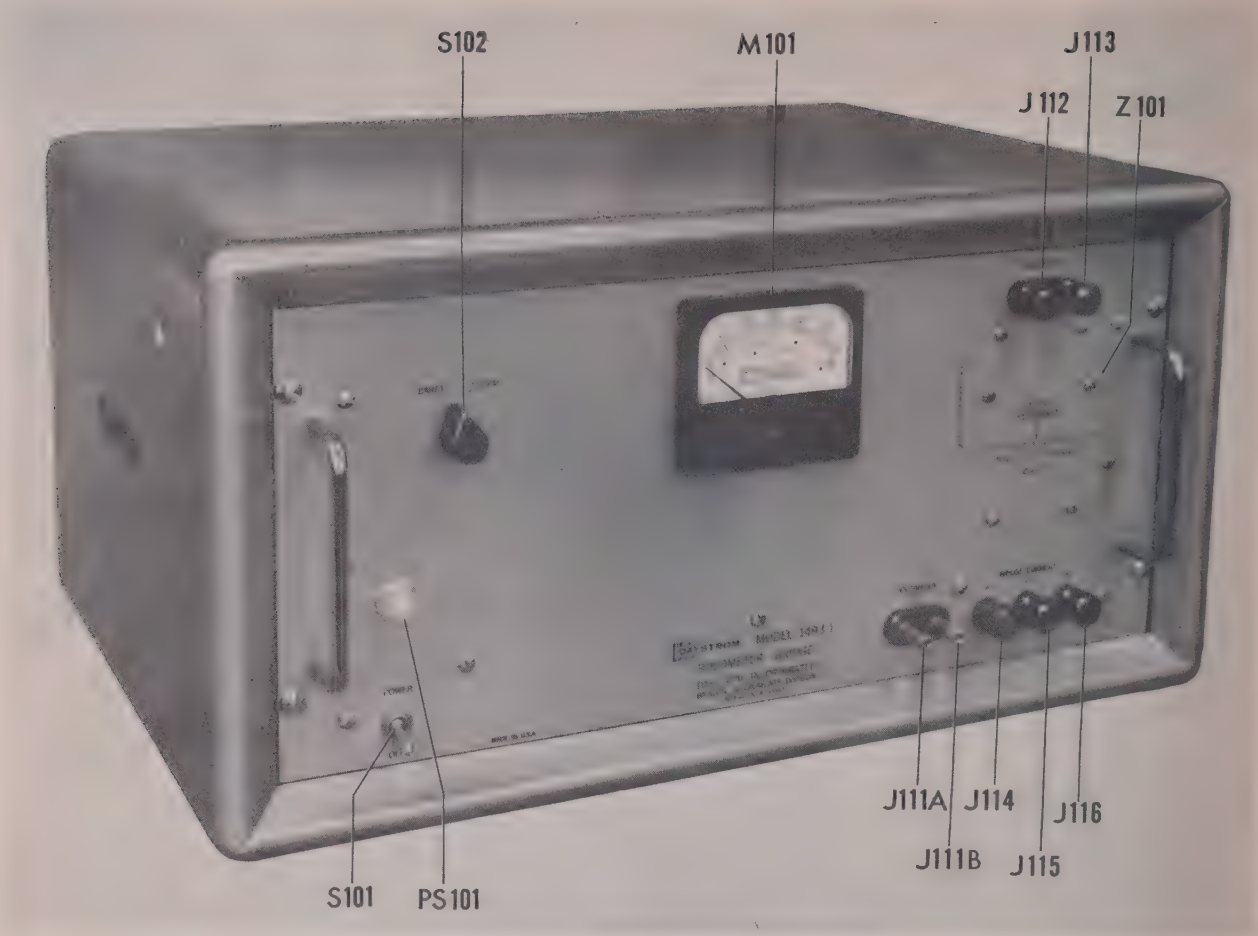


Figure 8. Bolometer Bridge Front Panel

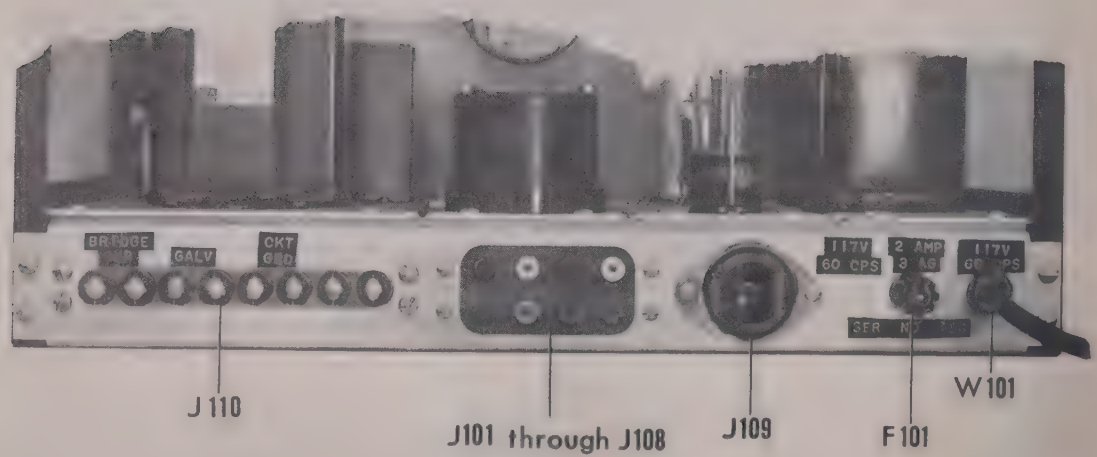


Figure 9. Bolometer Bridge-Rear Chassis Section

SYMBOL	NAME	FUNCTION
J111A and J111B	Terminal Assembly, BOLOMETER TEST	Connects bolometer terminals through a high-side 0.01 mfd capacitor.
J112 and J113	Binding Post BOLOMETER	Bolometer mount connections.
J114, J115 and J116	Binding Post BRIDGE CURRENT	J114 & J115 deliver bridge current to external instruments for accurate measurements. J116 is for a reference current generator.
M101	Meter, Bridge Current	Indicates total bridge current (twice the bolometer current) at a low accuracy (2%). Primarily for use as a start-up monitor.
S101	Toggle Switch, POWER-OFF	Controls power supplied to the Bolometer Bridge from the power line.
S102	Selector Switch, BARET-THERM	Sets bridge for the type of bolometer element connected. Reverses the feedback loop polarity.
W102	Cable, Bolometer	An accessory cable used to connect a bolometer to the bridge (see Figure 1.). The loop resistance is 0.036 ohms when the plug end is coupled to a short-circuited jack. Allow for this resistance when taking accurate measurements.
Z101	Network, Standard Resistance	Within the cover plate are terminal posts of the standard resistance network. Links connect the internal standard reference resistors for 200, 100 and 50 ohms. The top binding posts, normally linked together, are used to connect a suspension galvanometer for observing the bridge balance error. A movable marker on the cover plate indicates the internal connections (i.e., 50, 100 or 200 ohms). Refer to the schematic diagram in figure 5 on the network unit for the desired resistance selection.
DS101	Lamp, Neon	Indicates when instrument power is on.
		FRONT PANEL
F101	Fuse	A 2-amp, 3 AG line fuse.
J101 thru J108	Jack, Pin	Eight color coded pin jacks located on the rear of the chassis. Used in checking and testing the unit (see Section IV).
J109	Receptacle	A female receptacle with grounding contact is used for accessory equipment, under control of the POWER switch, but not protected by the fuse.
J110	Terminal Strip	An eight-contact terminal strip whose functions are: 1. BRIDGE CUR terminals are connected in parallel with, and have the same function as, front panel terminals J114 and J115. 2. GALV terminals are in parallel with, and have the same function as, the top binding posts of standard resistance network Z101. By removing the link across the Z101 binding posts, a suspension galvanometer for observing the bridge connection error can be connected directly to the GALV terminals, thus eliminating the need for a front panel connection. 3. CTK GRD terminals normally are not linked together. They connect the front panel terminals marked ⏚ to line ground. The bridge connection is unnecessary if the instrument is connected to a grounded bolometer mount. 4. SPARE terminals are used if necessary to connect a bolometer or a special bridge reference resistance. If the terminals are used, connect No. 12 AWG leads from the terminals to the BOLOMETER binding posts or to the middle two binding posts under the front cover of Z101 network.
W101	Cable, Power	A three-conductor power cable with a three-prong plug directs power to the instrument. The third prong is for chassis ground.
		REAR CHASSIS

Figure 10. Bolometer Bridge Control and Terminal Functions

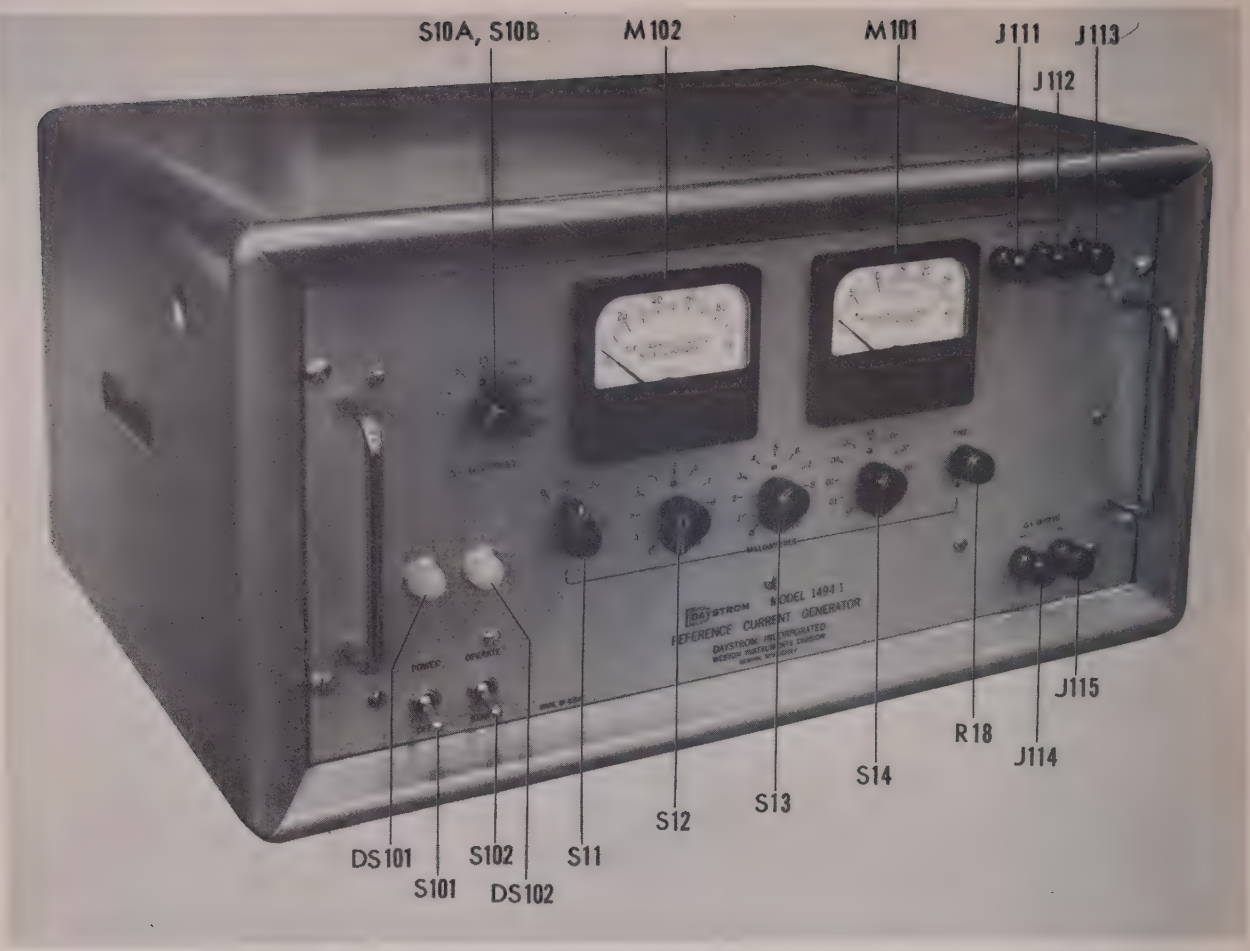


Figure 11. Reference Current Generator Front Panel

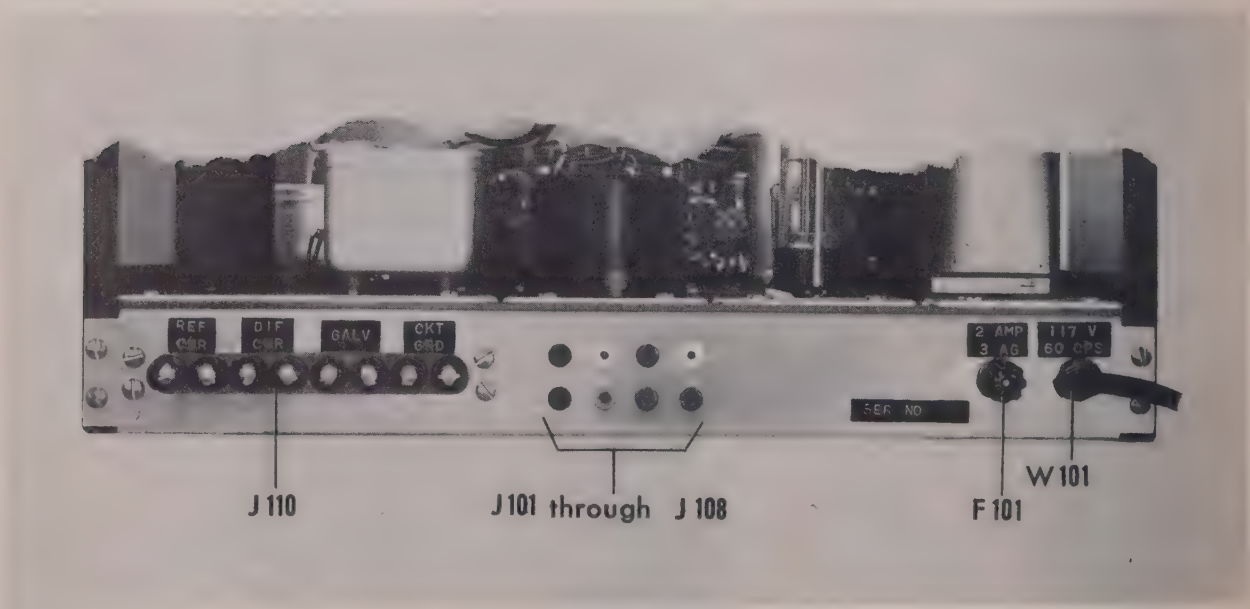


Figure 12. Reference Current Generator - Rear Chassis Section

SYMBOL	NAME	FUNCTION
*M101	Meter, Reference Current Milliamperes	Indicates output current level as adjusted by the mutual shunt. The sub-scale arc indicates the normal output current range of 3 to 30 MA.
*M102	Meter, Difference Current Microamperes	Indicates the difference current (Δ I) of 0 to 10,000 uA.
R18	Potentiometer	A 10 turn, FINE CONTROL potentiometer, used with S11 through S14, which changes the current by approximately 0.01 microamps per hundredth turn.
S10	Selector Switch, Δ I MULTIPLIER	A 9 position switch whose uses are: 1. 7 range selection for the Difference Current Meter. 2. START position for by-passing Difference Current Meter during start-up and preliminary adjustment. 3. EXTERNAL position to open the meter circuit when an external difference-current instrument is in use. Refer to the schematic diagram, figure 26, of the Δ I multiplier circuit.
S11 thru S14	Controls, Current-Setting Shunt	The MILLIAMPERES controls consist of 5 stepping switches in steps of .01 ma with an overall range of 20 to .01 ma. The stated current values are based on the mercury standard cell e.m.f. of 1.35 volts. Accurate measurements of the reference current can be made with external instruments. See figure 25 for the current-setting shunt diagram.
S101	Toggle Switch, POWER-OFF	Controls power supplied to Reference Current Generator from power line.
S102	Toggle Switch, OPERATE-START	With the switch in the START position, a resistance of 2700 ohms is connected in series with the reference cell to limit current from the cell to 1/2 Ma. In the OPERATE position, the resistance is short-circuited and the feedback is tightened for normal operation. Set switch to START until all preliminary settings are completed and the reference current is close to the required value.
J111, J112 and J113	Binding Post, REFERENCE CURRENT	Used for direct connection to the BRIDGE-CURRENT binding posts on the Bolometer Bridge when mounted as in figure 1. Before operating the Reference Current Generator, J111 and J112 must be loaded or the 3 binding posts must be connected as in figure 6.
J114 and J115	Binding Post, Δ I Output	Delivers the difference current (Δ I) to external current-measuring instruments when Δ I-MULTIPLIER switch is set at EXTERNAL.
DS101	Lamp, Neon	Indicates when instrument power is on.
DS102	Lamp, Neon	Indicates when switch S102 is in OPERATE position.

*The indicating meters are for convenience in set-up and monitoring. Power determinations derived from the meters may be in error by 5%. (See Section IV.)

FRONT PANEL

Figure 13. Reference Current Generator Control and Terminal Functions (Sheet 1 of 2).

SYMBOL	NAME	FUNCTION
F101	Fuse	A 2 amp 3 AG line fuse.
J101 thru J108	Jack, Pin	Eight color coded pin jacks located on the rear of the Chassis. Used in checking and testing the unit. (See Section IV.)
J110	Terminal Strip	An eight-contact terminal strip whose functions are: 1. GALV test terminals are in series with induction galvanometer G101. Normally the terminals are connected together by a jumper. By removing the jumper and connecting a suspension galvanometer, residual error current is indicated and amplifier gain can be determined. Refer to schematic diagram figure 23. 2. REF CUR terminals are in the reference-current output circuit. Normally, the terminals are connected together by a jumper. By removing the jumper and connecting an accurate external current-measuring indicator, reference current can be measured without making connections on the front panel. 3. DIF CUR terminals are in parallel with J114 and J115. An accurate external current-measuring indicator can be connected, instead of making front panel connections. 4. CKT GRD terminals permit connection of the front panel terminals marked ⏚ to line ground. If necessary, place a jumper across these terminals.
W101	Cable, Power	A three-conductor power cable with a three-prong plug directs power to the instrument. The third prong is for chassis ground.
	REAR CHASSIS	

Figure 13. Reference Current Generator Control and Terminal Functions (Sheet 2 of 2).

2. STEP-BY-STEP OPERATING PROCEDURES OF BOLOMETER BRIDGE

This paragraph contains the operating procedure for the Bolometer Bridge.

A. Place Bolometer Bridge on a vibration-free level surface.

B. Plug LINE CORD into a 117 volt, 50-60 cps power source.

C. Make sure that the arrow marker on the STANDARD RESISTANCE cover plate is set at the connected resistance value of 50, 100 or 200 ohms. Reset, if necessary, to the value of the connected bolometer.

D. Connect bolometer cable to BOLOMETER binding posts with black lead to ground and red lead to left binding post. Couple the plug end of the cable to the jack of the bolometer mount.

E. Connect BRIDGE CURRENT + and - binding posts to a current measuring instrument, or connect them together with a jumper.

CAUTION

Do not operate the Bolometer Bridge with the circuit open (see paragraphs 3 and 5 of this section).

F. Set BARET-THERM switch to the position of the type of bolometer connected. No damage to the Bolometer Bridge will result if the switch is not set correctly.

G. Set POWER-OFF switch to POWER. After 8 to 10 seconds a few milliamperes will begin to flow. After 15 seconds a time-delay relay will operate and the bridge current will rise momentarily to a value slightly higher than the bridge balance point, than snap back into balance. Allow an additional one minute warmup before proceding. The indicated current value is now I_1 in equation 1, Section II.

H. Apply r-f power to the bolometer. The indicated bridge current value will fall to a new value, I_2 in equation 1, Section II.

R_0 = Res. of Bolometer.

3. SYSTEM PRELIMINARY STEP-BY-STEP OPERATING PROCEDURE

This paragraph contains a step-by-step operating procedure for the Microwave Wattmeter. The test is made by using the built-in milliammeters to obtain the approximate end results. The use of external current-measuring instruments will be presented in subsequent paragraphs.

A. Place Reference Current Generator on a level surface and Bolometer Bridge directly on top of it as shown in figure 1.

B. Connect three jumper leads from BRIDGE CURRENT to REFERENCE CURRENT binding posts as shown in figure 1.

C. Connect bolometer cable to BOLOMETER binding posts with black lead to ground and red lead to left binding post.

D. Connect wire jumpers across GALV and REF CURRENT terminals of terminal strip J110 on the rear of the Reference Current Generator.

E. Connect Reference Current Generator power cable to Bolometer Bridge receptacle J109.

F. Couple the plug end of bolometer cable to a bolometer mount.

G. Set Bolometer Bridge POWER-OFF switch to OFF.

H. Plug Bolometer Bridge power cable into a 117 volt, 50-60 cps source.

I. Set Reference Current Generator POWER-OFF switch to POWER.

J. Set OPERATE-START switch to START.

K. Set BARET-THERM switch to the position corresponding to the type of bolometer connected.

L. Set Δ I MULTIPLIER switch to START.

M. After all initial connections and settings are made, set Bolometer Bridge POWER switch to POWER. The POWER switch pilot light on both units will glow.

N. After 15 seconds, the Bridge Current Meter will rise to twice the bias value and the Reference Current Meter will indicate the total value as the settings of the MILLIAMPERES switches.

O. Adjust the MILLIAMPERES switches so that the Reference Current Meter indicates the same as the Bridge Current Meter.

P. Set OPERATE-START switch to OPERATE.

Q. Gradually rotate Δ I MULTIPLIER switch counterclockwise from START to 1 and observe the Difference Current Meter. If the meter deflects from zero, reset the MILLIAMPERES switches to maintain current balance.

R. With the Δ I MULTIPLIER switch on position 1, the current will drift until the bolometer reaches a stable condition. Changes in ambient temperature also will cause noticeable drifting.

S. When stable and a balance condition exists, turn Δ I MULTIPLIER switch to 100.

T. Apply r-f power to the bolometer.

U. Rotate Δ I MULTIPLIER switch for maximum on-scale deflection of the Difference Current Meter. The Meter indication is $\Delta I = I_1 - I_2$.

V. Note the Reference Current Meter indication which is I_1.

W. Insert the values of Δ I and I_1 in the equation

$$P = \frac{R_0}{4} (2I_1 - \Delta I) \Delta I \qquad \text{(3 ref)}$$

to evaluate the substituted power in the bolometer.

X. When big changes in Bridge Current or Reference Current are made, rotate Δ I MULTIPLIER switch to START and continue with step O of this paragraph.

Y. When a big change in Reference Current is made, snap OPERATE-START switch to START to obtain high precision measurements.

Z. Set Δ I MULTIPLIER and OPERATE-START switches to START.

AA. Set Bolometer Bridge POWER-OFF switch to OFF.

4. APPLICABLE PROCEDURES

The procedure in paragraph 3 of this section was to familiarize the operator with the equipment. This same procedure is also used in applications where high accuracies is not of importance. In this case, accuracies of 2% of full scale meter reading are obtained by using the supplied equipment without external measuring instruments. In applications where higher accuracies are required, accurate external measuring instruments are used in lieu of the built-in meters to take advantage of the capabilities of the Engen Microwave Wattmeter. Paragraph 5 covers the equipment required to obtain accurate power measurements.

5. EXTERNAL CURRENT MEASURING EQUIPMENT

This paragraph covers the type of external measuring instruments used with this unit. Figure 14 lists external measuring equipment which may be used to attain the desired accuracies. The more accurate equipment used will directly result in a higher level of accuracy obtained.

NAME	DESIGNATION	APPLICATION	RANGE	ACCURACY
Potentiometer	Type K3 Leeds and Northrup	Where the calculated power accuracies of 0.01% is a requirement.	0 to 1.6V	.01% to .05%
Milliammeter	Model 1 Weston Instruments	Where the calculated power accuracies of 1 to 1.5% is a requirement.	30/15/7.5 ma	0.25%
Milliammeter	Model 325 Weston Instruments	Where the calculated power accuracies of .5 to 1% is a requirement.	30/15/7.5 ma	0.1%
Microammeter	Model 622 Weston Instruments	For Δ I measurements.	1000/500/ 200/100/50 ua	0.5%

Figure 14. External Current Measuring Equipment

The Engen Microwave Wattmeter measures r-f power with a calibrated bolometer and external instruments. It is used for accurate measurement of two direct currents in the range of 30 milliamperes to about 5 microamperes. The highest accuracy of current measurement is achieved by using precision standard resistors with a rated accuracy of 0.01% as shunts, and a high-quality potentiometer such as the Leeds and Northrup Type K-3. Lesser accuracies are achieved with portable instruments of 0.25% or 0.5% accuracy. The best values of shunt resistance or of milliammeter range depend on the amount of power to be measured and on the bolometer bias current.

In the measurement of r-f power values (which are large fractions of the total dissipation in the bolometer at balance) the Model 1493-1 Bolometer Bridge can be used alone. Currents will range in value between twice the bias current and some value near bias. The bridge-current values must be measured for a single power determination (See equation 1, Section II). They are I_1 (before applying r-f power) and I_2 (after applying r-f power) to the bolometer. They may be measured with a single instrument having suitable ranges, connected to the BRIDGE CURRENT binding posts. With a Weston Model 1 Milliammeter, power with accuracies of 1 to 1.5% is achieved. Greater accuracies are achieved by using the Model 325 laboratory standard milliammeter. For highest accuracy using precision standard shunt resistors with a potentiometer, choose shunt resistances which will produce the highest possible potential differences without exceeding the range of the potentiometer (usually 1.6 v). High resistances will produce the best resolution in the potentiometer and will make stray emf's insignificant. For instance, to measure the design-maximum value of 30 ma, either a 10 ohm $\pm$ 0.01% shunt yielding a potential of 300 mv, or two 100 ohm units in parallel yielding a potential of 1.5V, is recommended. If the current falls below 16 ma, resistance should be increased to 100 ohms $\pm$ 0.01%. If National Bureau of Standards Type resistors are used, their current ratings will not be exceeded by this procedure. Decade resistance boxes should not be used because their accuracy is inadequate.

When the Model 1494-1 Reference Current Generator is used (particularly for measurements of power below a few milliwatts) reference current I_1 and difference current Δ I are best measured with separate instruments. The Weston Model 1 or Model 325 Milliammeter is recommended for measuring I_1 where moderate accuracy is sufficient. The 10 ohm and 100 ohm precision standard resistors are used with a potentiometer for highest accuracy.

For power measurements of moderate accuracy, the Weston Model 622 Microammeter (high resistance type) is recommended for measuring Δ I. For measuring Δ I with high accuracy, the resistance of the shunt should normally be 100 ohms $\pm$ 0.01%. Higher resistances up to 1000 ohms may be used, but high resistance loads the amplifiers and tends to reduce gain.

Difference current Δ I may have any value between a few milliamperes and 50 microamperes or less. The range of values can be anticipated by means of the equation under Figure 15.a. For example, if bolometer resistance R_0 is 200 ohms at a bias current ($1/2\ I_1$) of 8.5 ma, the substituted d-c power in microwatts will be

$$P = 50\ (34 - \Delta\ I)\ \Delta\ I \qquad (5)$$

At relatively low power levels

$$P \approx 1.7\ \Delta\ I \qquad (6)$$

where P is in microwatts and Δ I is in microamperes. In other words, Δ I in microamperes is about 60% of the r-f power in microwatts.

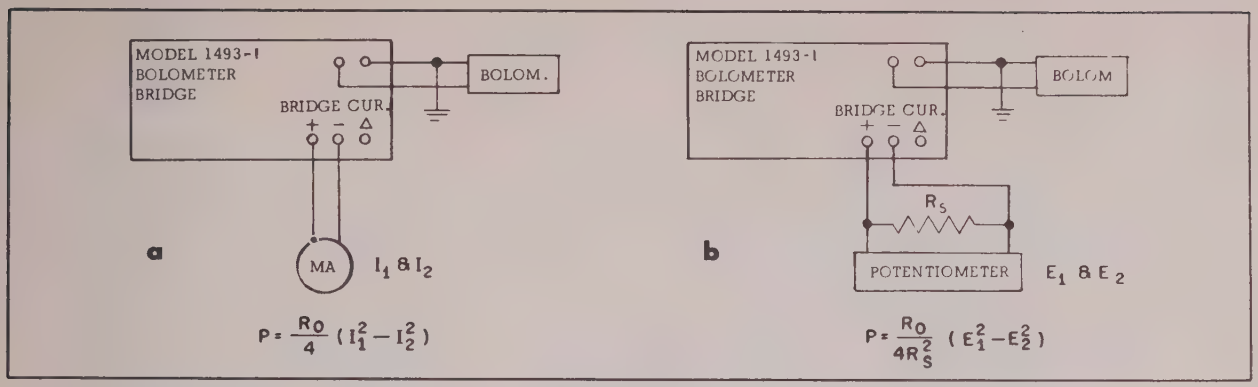


Figure 15. Connection of Measuring Instruments to Bolometer Bridge.

6. CONNECTIONS FOR ACCURATE CURRENT MEASUREMENTS

The connection of a milliammeter for measuring I_1 and I_2 in a bolometer bridge alone is shown in figure 15.a. Figure 15.b shows a precision shunt and potentiometer connected for making the same measurements with higher accuracy.

Figure 16 shows the connections for external instruments to a Model 1493-1 Bolometer Bridge combined with a Model 1494-1 Reference Current Generator. A milliammeter and microammeter are shown connected in figure 16.a. Figure 16.b shows a precision shunt and potentiometer connected to measure the reference current for I_1. (The reference current must be adjusted to balance the initial bridge current.) Figure 16.c is similar to 16.b except that initial bridge current I_1 is measured directly. (The reference current may be offset from the initial bridge current.) The same power equation applies to diagrams 16.b and 16.c. Since the reference current must be adjusted to a very high degree of precision with respect to the bridge current (particularly for the measurement of very low power levels) the inherent precision of methods 16.b and 16.c is the same. The choice between them will be based on practical considerations and operator's preference. In the first method (16.b), all adjustments including r-f power injection can be made before the currents are measured. In making power measurements of moderate accuracy with two portable standard milliammeters, it is convenient to read I_1 and ΔI in a single operation. If it is not desired to make the reference current exactly equal to I , the value of the reference current is unnecessary and the initial bridge current must be measured directly according to the second method. For instance, if drift during measurement is a problem, it may be helpful to set the reference current slightly above initial bridge current, I_1, so that the initial difference current is offset slightly above zero. After measurements are completed and r-f power has been returned to its initial level, the effect of drift can be observed as a departure in either direction from the initial amount of offset.

R-f power in the bolometer need not be zero when the reference current is adjusted. The reference current generator makes it possible to measure small increments of power above any desired initial level within the range of the bridge and bolometer. In general, reference current is adjusted to equal--or to be offset from--the bridge current with r-f power at any chosen initial level, which may or may not be zero. When r-f power to the bolometer is increased, and current measurements have been completed according to one of the methods previously described, the power equation evaluated the increase of power. This technique is particularly useful in the calibration of attenuators.

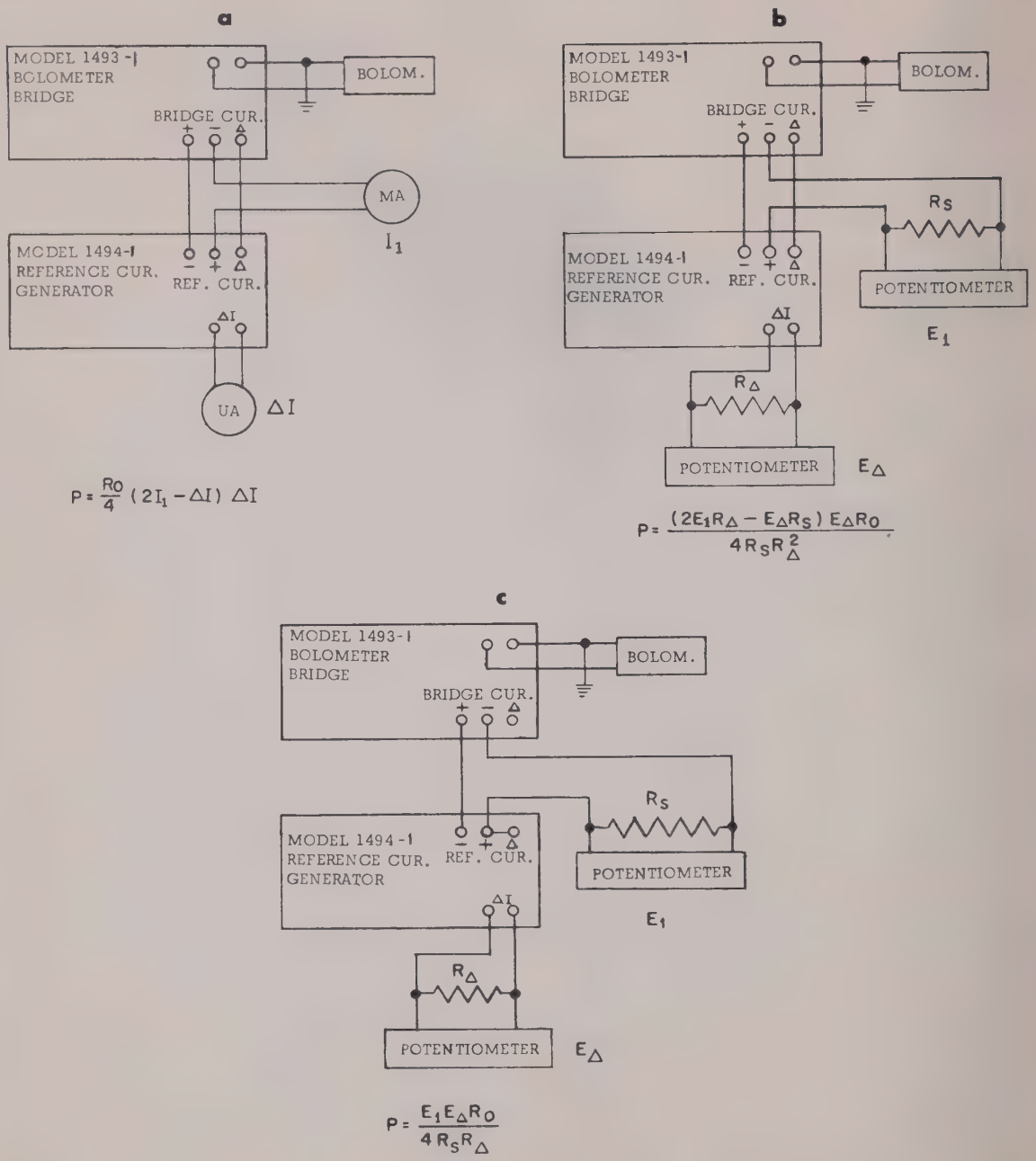


Figure 16. Connection of Measuring Instruments to System.

SECTION IV MAINTENANCE

1. TROUBLE SHOOTING

General trouble shooting of circuit or component failures is similar to that for regular electrical equipment. Usual ohmmeter checking for circuit continuity and grounds, shorted capacitors, resistors, etc., will disclose the troubles. Figure 17 is a trouble shooting chart designed to aid in locating and repairing troubles most likely to be encountered. Also refer to figures 18 and 19 for proper circuit voltages.

SYMPTOM	CAUSE	REMEDY
Bridge Current Meter deflection limited to 1 ma	Open barretter.	Replace barretter.
	Baret-Therm switch set improperly.	Reset to proper position.
	Defective Model 1401 Galvanometer.	Return to factory for repair.
No deflection of Bridge Current Meter or Reference Current Meter	Open circuit in equipment connected across Bridge output or Reference Current Generator output terminals.	Check output circuit for continuity.
	Defective power supply.	Check for 225 v at red and black jacks. If low, or no reading, check power supply tubes and silicon rectifiers.
	Defective power amplifier.	Check power amplifier tube (6AQ5/6005) V104.
Bridge Current Meter deflects offscale	Open Thermistor.	Replace thermistor.
	Amplifier not properly aligned.	Realign amplifier per Section IV-3.
Bridge Current Meter or Reference Current Meter reading unstable	Amplifier not properly aligned.	Realign amplifier per Section IV-3.
	Defective Model 1401 Galvanometer.	Return to factory for repair.
Reference Current Meter reads offscale	Amplifier not properly aligned.	Realign amplifier per Section IV-3.

Figure 17. Trouble Shooting Chart

2. TEST VOLTAGES

Both the bolometer bridge and the reference current generator have eight (8) test jacks, identified by their color codes, located on the rear chassis. Figure 18 gives test voltage value at the points listed.

Test Point	Model 1493-1	Model 1494-1
Brown (HI) to Green	-	1.35 volt with power on
Yellow to Brown	32 volt swing for 3-30 ma output with 0 volt at 6 ma	30 volt swing for 3-30 ma output with 0 volt at 15 ma
Green (HI) to Brown	18 volts plus a voltage equal numerically to output current in ma. (Thermistor Setting)	-
Green (HI) to Brown	18 volts plus a voltage equal numerically to output current in ma. (Barretter Setting)	-
White (LO) to Black	150 volts	-
White (HI) to Green	-	1.35 volt
Black	Internal chassis ground	Internal chassis ground
Orange (HI) to Black	350 volts at 117 volts line, output shorted	350 volts at 117 volts line, output shorted
Red (HI) to Black	225 volts	225 volts

Figure 18. Test Voltage Points of Color Coded Terminal Strip on Rear Chassis

Figure 19 lists test voltages (± 20%) at the listed points with line voltage at 117 volts and output at 30 ma and 3 ma. These voltages are measured for the tube pin to the black pin jack of the color coded terminal strip.

TUBE CODE	PIN NUMBER	AT OUTPUT CURRENT OF 30 MA	3 MA
V101	1&4	230 volts	190 volts
V102	1	-4	-4
V102	5	230	190
V102	6	120	140
V601	1	145	145
V601	2	0	0
V601	3	1.5	1.5
V601	6	225	225
V601	8	1.4	1.4
V602	2	33	33
V602	5	225	225
V602	6	225	225
V602	7	0	0
V603	1	+7.4	-8.3
V603	2	-67	-95
V603	5	+ 49	+0.5
V603	7	-67	-105

Figure 19. Tube Pin to Black Pin Jack Voltage Measurements.

3. AMPLIFIER ALIGNMENT

A. General

The Amplifier has four trim adjustments to the operating frequency of 200 kc; the three transformers and the galvanometer field. In normal service these should be permanent. In the event of replacement, trim adjustments may be made with proper equipment. The discriminator transformer trim serves as the operating frequency reference. As a replacement part it is supplied preadjusted to 200 kc. Trimming procedure normally involves adjusting the input and interstage transformers and the galvanometer field to alignment with the discriminator transformer.

B. Discriminator Adjustment

The discriminator transformer T603 must be tuned to 200 kc ± 2%. Tuning the discriminator transformer requires a reference source of 200 kc and the alignment procedure is as follows:

(1) Remove V601 and V104.

(2) Apply approximately 5 volts at 200 kc ± 2% to the control grid of V602 (blue pin jack) and floating ground (black pin jack).

(3) Connect 1-0-1 ma milliammeter across yellow and brown jacks. Trim discriminator transformer to zero the output current.

C. Trimming Adjustments

(1) Remove output tube V104. Replace V601 (12AX7) with a similar testing tube type having the 6-7-8 pins removed.

(2) Trim interstage transformer T602 to zero output current.

(3) Replace testing tube with the regular 12AX7 tube. Connect an oscilloscope or a low-range vacuum tube voltmeter to the galvanometer moving coil (C_1 to ground and C_2 high) using a shielded or twisted-pair line. A 200 kc voltage will be observed.

(4) Trim input transformer T601 to maximize the a-c voltage across C_1 and C_2. The tuning of this stage is very broad and uncritical.

(5) Remove 1-0-1 milliammeter. Replace V104. Retrim T602 to bring 200 kc voltage across C_1 and C_2 to a minimum. If the primary adjustment (2 above) has been well made, retrimming will not require much more than a 1/4 turn of the tuning slug.

4. BOLOMETER BRIDGE

A. Standard Resistance Network

Follow the procedure in the following steps to remove the Standard Resistance Network for re-certification. (See figure 5.)

(1) Unsolder lead to terminal #5 on top of the standard resistance box. Do not unsolder any other connections.

(2) Remove 4 leads from the rear BOLOMETER binding posts, and 3 leads from the rear studs of the aluminum bracket.

(3) Remove 4 screws holding front panel to network and lift the network free of the BOLOMETER BRIDGE unit.

(4) Measure the resistance between the following terminals on standard resistance box with a Wheatstone bridge.

across 1 and 3 = 100 ohms $\pm$ 0.01%
across 7 and 9 = 100 ohms $\pm$ 0.01%
across 4 and 5 = 200 ohms $\pm$ 0.1%
across 5 and 6 = 200 ohms $\pm$ 0.1%

Glenn F. Engen's discussion on this subject matter (see appendix) shows that inequality of the two ratio arms of 2% will produce an error in power measurement of 0.01%, because unequal divisions of bridge current produces a compensating effect.

B. Leakage Current. Leakage current is a source of error and the measurement of this leakage is given in the following steps. (Refer to figure 4 for the Basic Circuit Bolometer Bridge and figure 20 Leakage Test Circuit.)

(1) Disconnect the lead from the minus (-) terminal of the Bridge Current Meter.

(2) Connect a 1000 ohm 1 watt resistor resistor between minus meter terminal and BRIDGE CURRENT (Δ) binding post.

(3) Connect a calibrated suspension galvanometer with a sensitivity of 0.01 uA per millimeter to BRIDGE CURRENT (+) and (-) binding posts. Connect a variable shunt across the galvanometer.

(4) Set the POWER-OFF switch to POWER. It is not necessary to connect a bolometer for this test.

(5) Note the BRIDGE CURRENT meter for an indication, or off scale.

(6) If necessary, adjust the Model 1401 galvanometer by turning the slotted zero corrector located on the galvanometer cover to obtain a meter reading of 10 to 30 ma.

(7) If the leakage current exceeds 0.3 microamperes, steps 8 through 10 list the probable causes of excessive leakage.

(8) A stray piece of metal grounding the floating chassis or the secondary circuit of the isolation transformer.

(9) Leakage from the galvanometer field coils to the amplifier input circuit. This can be reduced by disconnecting the leads from the F_1 and F_2 terminals on the galvanometer.

(10) A defective isolation transformer. Test isolation transformer T102 by disconnecting the secondary leads of T102 from primary terminals 1 and 2 of plate and filament transformer T101. Resistance between the secondary leads and ground should exceed 300,000 megohms (3×10^{11} ohms) at 500 v test voltage. Use a General Radio Type 544-B Megohm Bridge for this test. Replace the isolation transformer if defective.

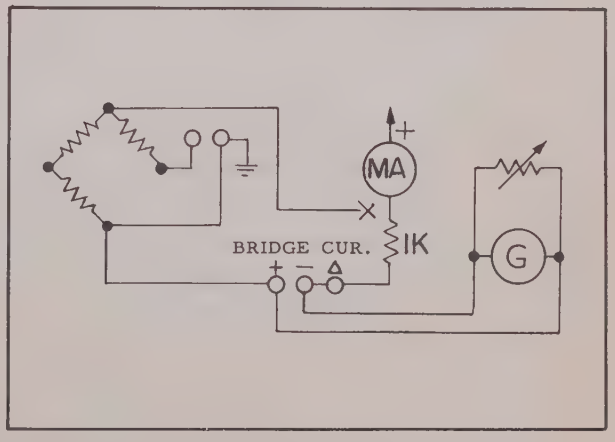


Figure 20. Leakage Test Circuit.

C. Noise in Bolometer. Randomly variable noise voltages across the bolometer are an important factor in establishing the low limit of power which can be measured with satisfactory accuracy. When the system is in operation, noise can be observed with an oscilloscope. The rms value can be measured with a vacuum tube voltmeter connected to the BOLOMETER TEST terminals located to the left of the BRIDGE CURRENT binding posts. Not more than 2 mv should appear across the test terminals.

D. Gain. Current gain in the whole amplifier should be between 100,000 and 300,000. If it is too low, resolving power will suffer; if it is too high, the system may become unstable in connection with some thermistors. Gain is $(I_1 - I_2) / \Delta I_g$, where I_1 and I_2 are the same as in equation 1, Section II and others, and ΔI_g is the change in amplifier input current which occurs when bridge current changes from I_1 to I_2. These quantities are measured as follows:

(1) Remove top link under STANDARD RESISTANCE cover. Connect a suspension galvanometer to the binding posts exposed or to the GALV terminals in back. Galvanometer sensitivity is approximately 0.01 microamperes per mm. Resistance is as low as possible (less than 50 ohms).

(2) Connect a jumper across the BRIDGE CURRENT + and - binding posts.

(3) Connect any kind of bolometer to the BOLOMETER binding posts.

(4) Set BARRETTER-THERMISTOR switch correctly and apply line power.

(5) Observe the indications of the BRIDGE CURRENT MILLIAMMETER (I_1) and the galvanometer.

(6) Deliver r-f power to the bolometer and adjust the level so that bridge current is reduced to about 1/2 of I_1. The new value is I_2. The reduction in bridge current can be effected without using r-f power by varying the resistance of the reference arm (R_0) of the bridge. With a 200 ohm barretter connected, the reference arm resistance is reduced by shunting with several hundred ohms until the bridge current falls to approximately 1/2 its initial value. This is done by connecting a decade resistance box to the middle pair of terminals under the STANDARD RESISTANCE cover (See Figure 22).

(7) Observe the deflection of the galvanometer from its original position. Apply the galvanometer calibration factor to obtain ΔI_g.

(8) Calculate the current amplification factor from the equation

$$\alpha = (I_1 - I_2) / \Delta I_g \qquad (7)$$

If α is less than 100,000, test the tubes and other amplifier components and voltages. If they are satisfactory, test the DC Inductronic® Amplifier following the procedure in paragraph 3 of this section.

Special damping elements have been incorporated in the amplifier to maintain stability. However, oscillation may occur with a thermistor having particularly unfavorable time lag. This can be observed with an oscilloscope connected to the BOLOMETER TEST terminals. Instability will be displayed in the form of oscillations with a frequency of about 60 cps and an amplitude considerably in excess of the allowable noise level. The allowable noise level across a 200 ohm bolometer is 2 mv.

To reduce gain remove the cover from the galvanometer and push the small strip of bronze wrapped around one of the cover posts toward the surface of the magnet pole piece.

If none of these procedures brings the gain within a satisfactory range, return the equipment to Daystrom-Weston.

E. Galvanometer Spring Setting. The torsional constant of the moving-element springs in the Model 1401 Induction Galvanometer is extremely low, yet its effect is noticeable. If the zero corrector is rotated when performing the gain test described in paragraph 4.D. above, the magnitude of amplifier input current I_g will change. The correct setting is that which makes the ratio of bridge current I_b to galvanometer current I_g constant and equal to the current gain. The reason for this is as follows:

Equation 4 in Engen's discussion on the self-balancing bolometer bridge applies a correction factor to the basic equation for power. Two terms in this factor are functions of input current and gain. The most important one in determining how much error will be introduced into the measurement as a result of limited gain and improper zero setting can be reduced to the form

$$Q = \left(\frac{1}{\alpha} - \frac{I_g}{I_b}\right) \qquad (8)$$

where Q is a variable of infinite value, (so long as bridge current is not reduced to zero), α is current gain, I_b is bridge current, and I_g is the corresponding amplifier input current. Before the galvanometer has been adjusted, the relation of I_g to I_b may be as represented by one of the two sloping dashed lines in Figure 21. In this figure, I_g has a positive or negative residual value, I_{go}, where the extrapolated line intersects

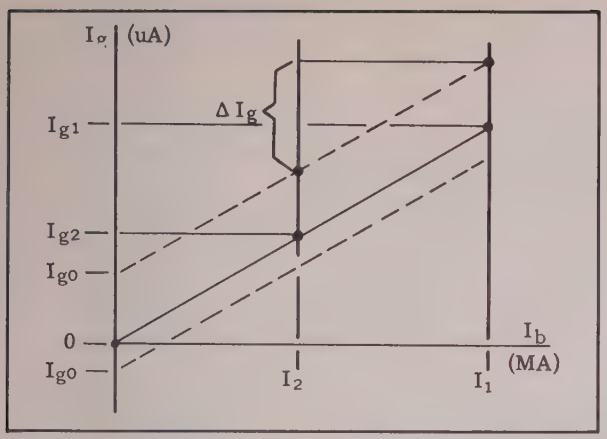


Figure 21. Relation of input current to bridge current.

the axis of ordinates. Assuming a linear transfer characteristic,

$$\infty = \frac{I_1 - I_2}{\Delta I_g} = \frac{I_b}{I_g - I_{go}} \qquad (9)$$

The zero corrector can be set to make $I_{go} = 0$ by adjusting it so that I_{g1} and I_1, and I_{g2} and I_2 are co-ordinates of two points on the solid line passing through the origin. Then $I_b / I_g = \infty$, and the error term vanishes (under ideal conditions) even for an amplifier of finite gain and for relatively small values of I_2.

In other words, correct adjustment of the galvanometer springs produces a cancellation of the effect of the error (represented in this case by I_g) which is inherent in proportional-control systems.

F. Resolving Power

In most applications of the bolometer bridge, the effect of friction and moving-element fall-over in the Induction Galvanometer will be imperceptible. Occasionally, however, when extremely small quantities of power or power change are to be measured, it is important to know the actual resolving power of the bridge. This is necessary since friction and fall-over effect is a major limitation on system performance under these conditions.

To evaluate resolution, connect the bolometer bridge and the reference current generator together as shown in Figure 16.a. The external bridge-current milliammeter, labeled MA in the diagram, may be omitted and replaced by a jumper. Replace the microammeter labeled UA with a galvanometer having a sensitivity of about 0.01 ua per mm and a resistance below 200 ohms. Any kind of bolometer may be used if the temperature can be stabilized so that drift of Δ I arising from temperature influence on the bolometer is limited to 0.05 microamperes. When the system has warmed up sufficiently to be stable for a short time, Δ I is reduced to some easily-noted value near mid-scale on the galvanometer. A momentary change in Δ I of a few tenths of a microampere is effected by a momentary injection of r-f, a change of bridge arm resistance, or if the bridge case is jarred. Upon removal of the disturbance, Δ I will return to its initial value. The deviation from this value is the quantity of interest. Repeat the test several times to establish the maximum deviation possible. (The effect of drift must be deducted.) Resolution in terms of power is evaluated by introducing the deviation as Δ I and the BRIDGE CURRENT MILLIAMMETER indication as I_1 in the power equation under Figure 16.a.

The rated bridge resolution is 0.1 microwatt. If the resolution exceeds this value, clean or replace the pivots and jewels of the galvanometer.

5. REFERENCE CURRENT GENERATOR

A. Gain

Gain is measured according to the procedure in paragraph 4.D. of this section with the following revisions.

(1) Remove jumper across GALV terminals and connect monitoring galvanometer here.

(2) Connect a jumper or load across REFERENCE CURRENT (+) and (-) binding posts. (See Figures 6 and 24). Current gain should be at least 200,000 and is not likely to be too high. If it is too low, examine the equipment per paragraph 3.D. of this section.

B. Noise

Noise and a-c component output of the generator is examined by connecting a load resistance of 1000 ohms, 1 watt, across the REFERENCE CURRENT (+) and (-) binding posts, and an oscilloscope or vacuum tube voltmeter across the load with the ground side to the (-) binding post. The total rms noise and a-c voltage must not exceed 0.3% of the d-c voltage across the load. With a 1000 ohm load, this voltage must not exceed 90 mv at an output of 30 ma d-c, or 9 mv at 3 ma d-c.

C. Galvanometer Friction

Effects of friction in the galvanometer of the reference current generator can be observed when testing bolometer bridge resolution. (See paragraph 4.F. of this section.) If bridge current is kept constant and reference current is momentarily changed and then returned to its initial value, Δ I also should return to its initial value within the same limits as required of bridge current. If it does not, follow the procedure in paragraph 4.F. of this section.

SECTION V ELECTRICAL SCHEMATIC DIAGRAMS

This section contains all electrical schematic diagrams pertaining to the Model 1493-1 Bolometer Bridge and Model 1494-1 Reference Current Generator.

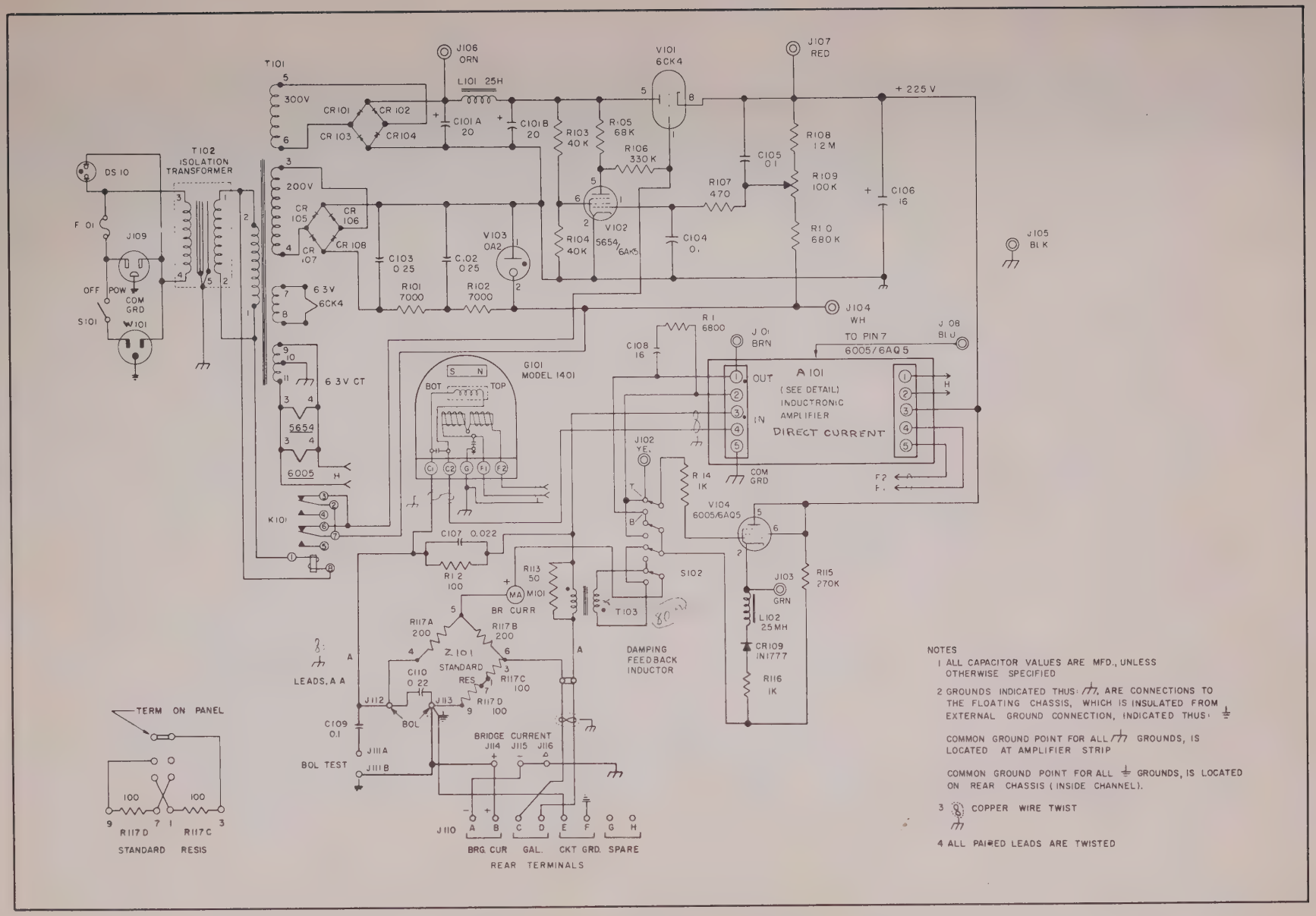


Figure 22. Schematic Diagram of Bolometer Bridge

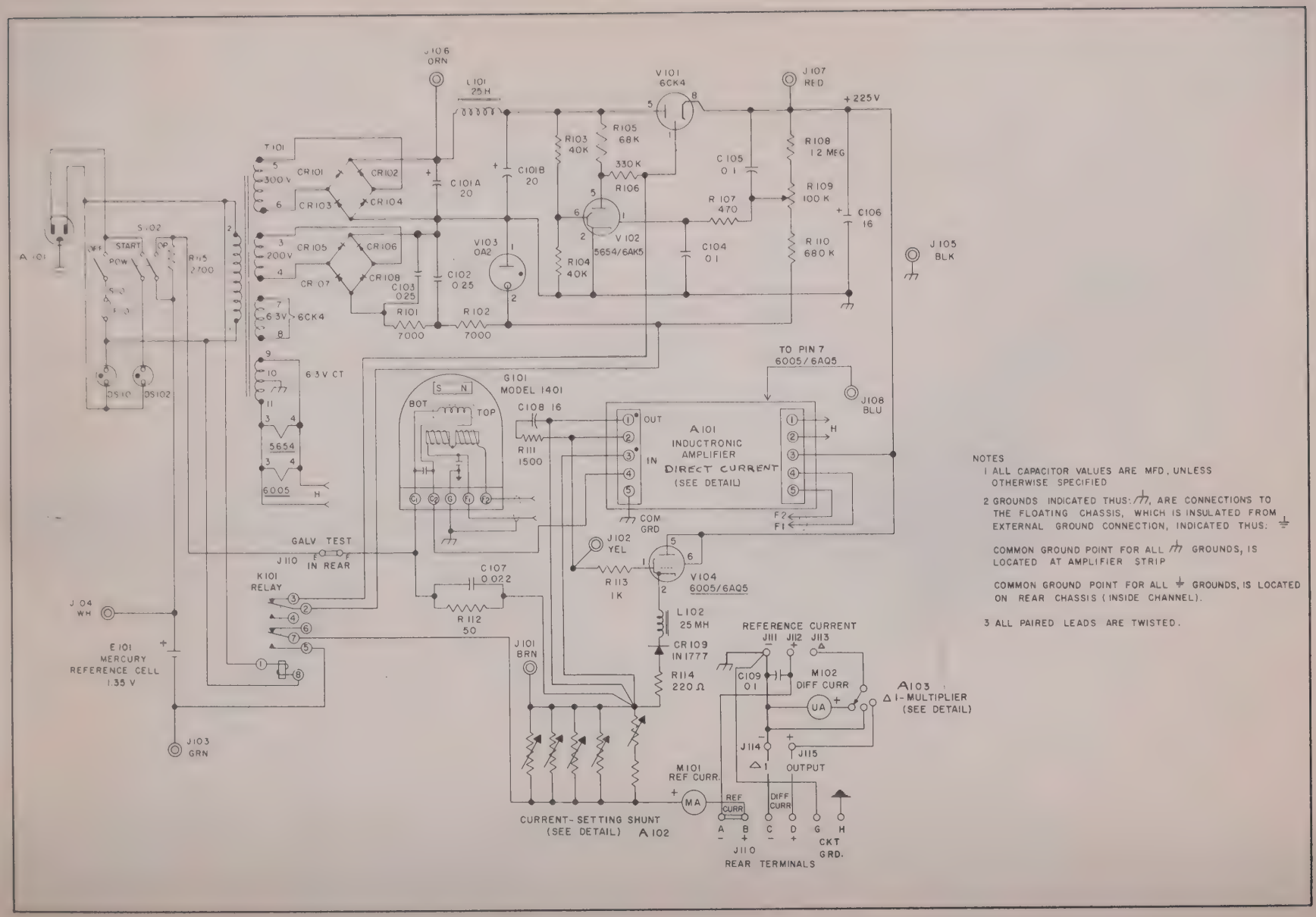


Figure 23. Schematic Diagram of Reference Current Generator

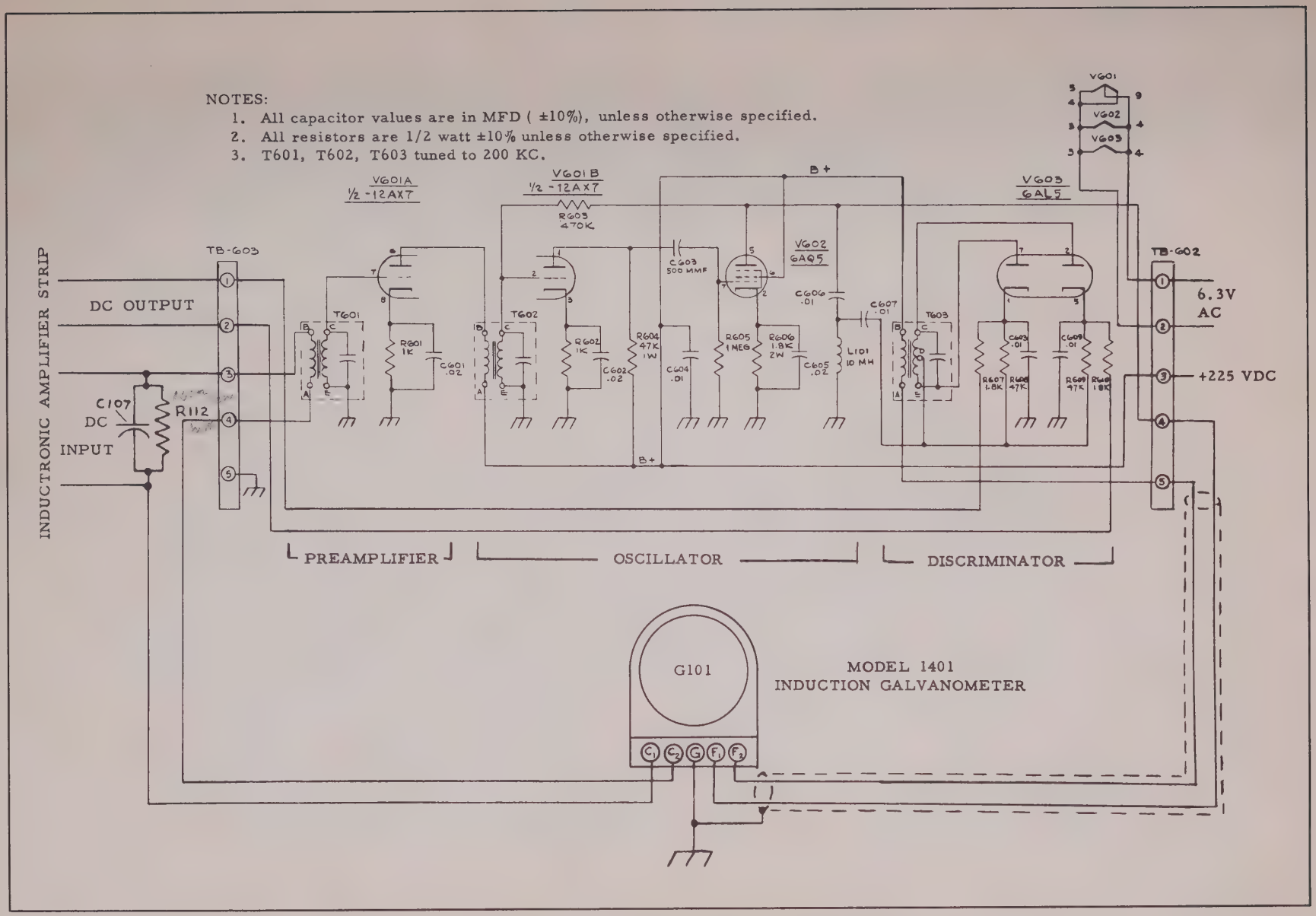


Figure 24. Schematic Diagram of Direct Current Inductronic® Amplifier

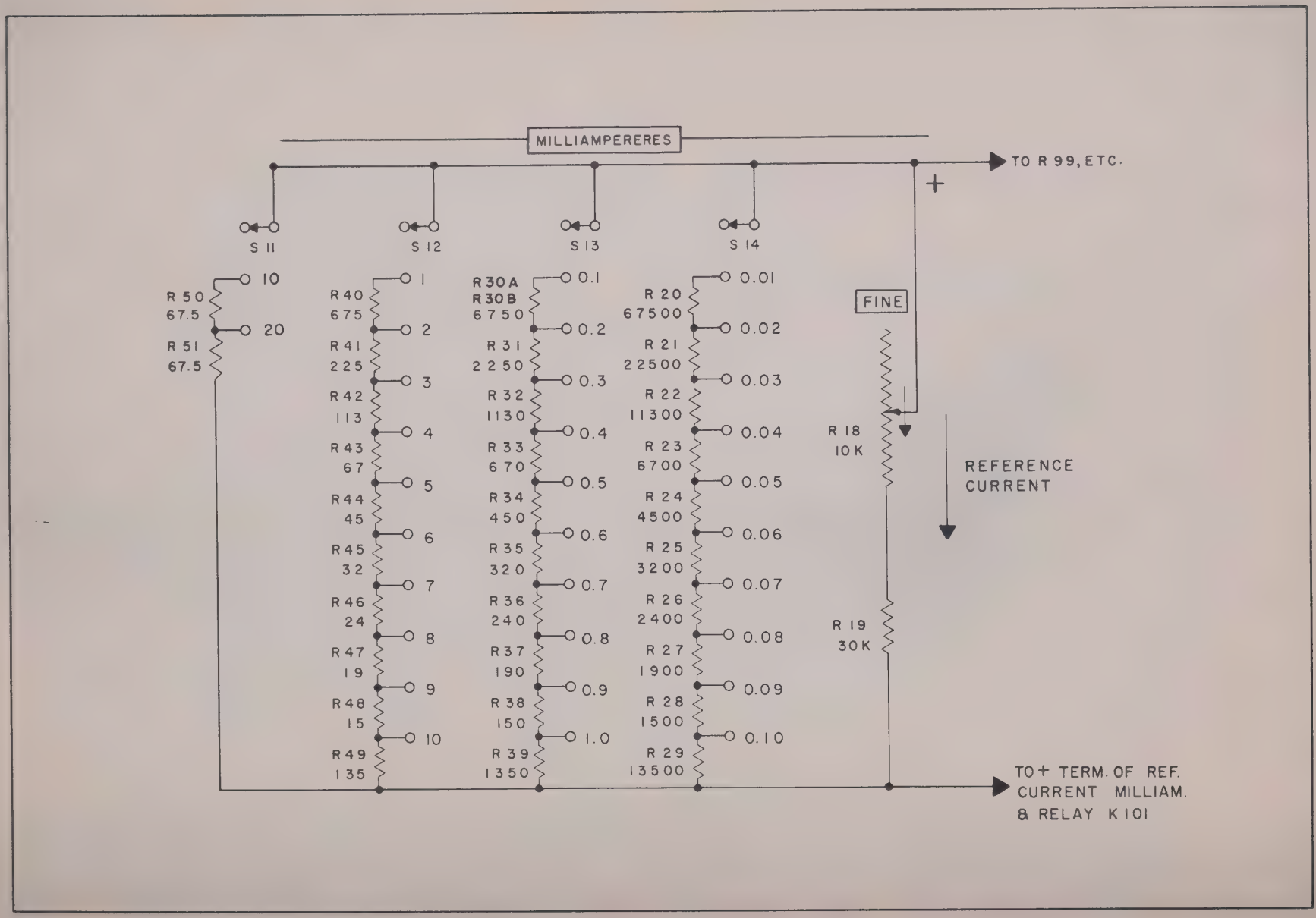


Figure 25. Schematic Diagram of Current Setting Shunt (A102)

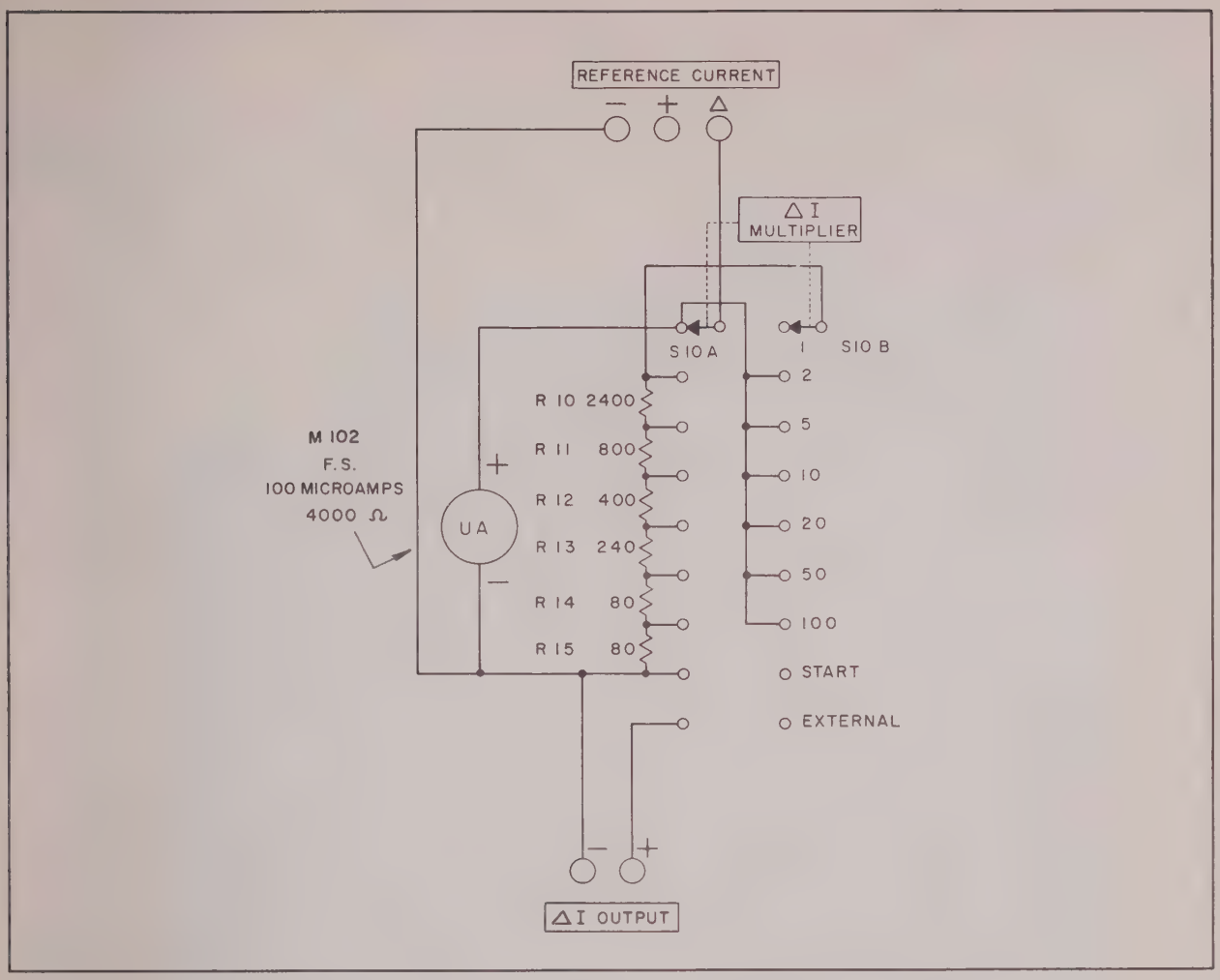


Figure 26. Schematic Diagram of ΔI Multiplier Circuit (A103)

SECTION VI REPLACEMENT PARTS LIST

The replacement parts list contains the major electrical components of the unit. Photographic illustrations are included to aid in locating and identifying parts.

When ordering parts, specify the model number, part number and a complete description of the part.

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
A101	AMPLIFIER, DIRECT CURRENT: (Weston Model 9950 type 28)	186610-901	1
C101A, C101B	CAPACITOR, FIXED, ELECTROLYTIC: 20-20 UF, 450 vdcw (Cornell Dubilier cat. no. UPB-14)	ND 60430-001	1
C102	CAPACITOR, FIXED, PAPER DIELECTRIC: 0.25 UF, ± 10%, 400 vdcw (Arco-Elemenco part no. 4DP-5-254)	ND 60425-001	2
C103	CAPACITOR, FIXED, PAPER DIELECTRIC: Same as C102		
C104	CAPACITOR, FIXED, PAPER DIELECTRIC: 0.1 UF, ± 10%, 600 vdcw (Arco-Elemenco part no. 6DP-4-104)	ND 60432-001	3
C105	CAPACITOR, FIXED, PAPER DIELECTRIC: Same as C104		
C106	CAPACITOR, FIXED, ELECTROLYTIC: 16 UF, 450 vdcw, (Cornell Dubilier cat. no. BR1645)	ND 60433-001	1
C107	CAPACITOR, FIXED, CERAMIC DIELECTRIC: 0.022 UF, ± 20%, 200 vdcw (Erie part no. 896-.022)	ND 60445-001	1
C108	CAPACITOR, FIXED, PAPER DIELECTRIC: 16 UF, ± 20%, 150 vdcw (Astron cat. no. MD-1.5-16M)	ND 60444-001	1
C109	CAPACITOR, FIXED, PAPER DIELECTRIC: Same as C104		
C110	CAPACITOR, FIXED, PLASTIC DIELECTRIC: 0.22 UF, ± 10%, 200 vdcw (Cornell Dubilier cat. no. PM2P22)	ND 60454-001	1
CR101 thru CR108	SEMICONDUCTOR DEVICE, DIODE: Type IN 1489	ND 60422-001	8
CR109	SEMICONDUCTOR DEVICE, DIODE: Type IN 1777	ND 60423-001	1
DS101	LAMP, GLOW: neon, 0.25 watt, 115 vac (General Electric lamp no. NE-51H)	ND 60020-001	1
F101	FUSE, CARTRIDGE: 2 amp (Littlefuse type 3AG)	ND 60453-001	1
G101	GALVANOMETER, INDUCTION: (Weston Model 1401 type 1)	132167	1
J101	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, brown, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-608)	ND 60462-001	1
J102	JACK, TIP: Silver plated beryllium copper contact, integral solder terminal, molded nylon body, yellow, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-607)	ND 60460-001	1
J103	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, dark green, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-604)	ND 60458-001	1

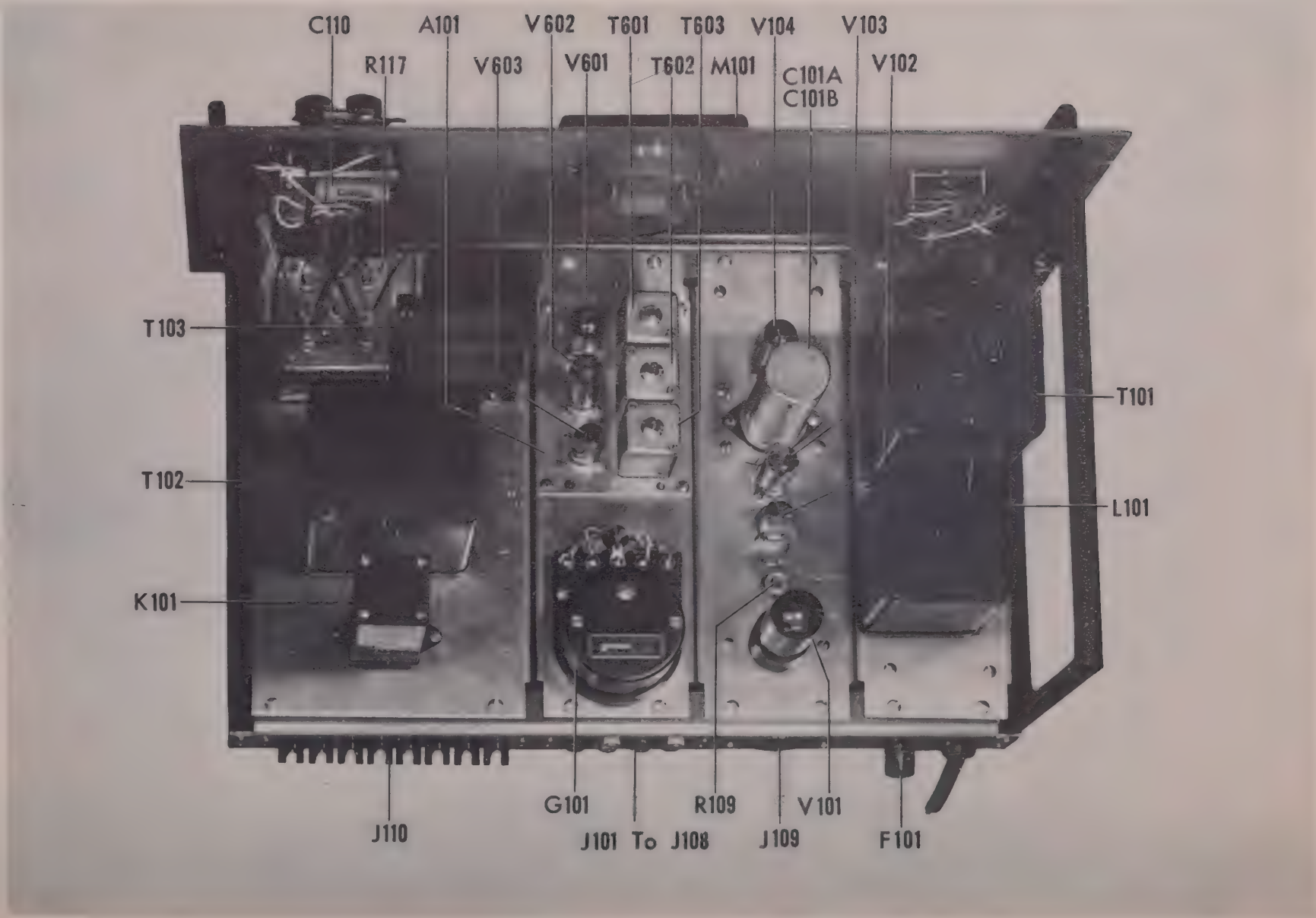


Figure 27. Top View of Bolometer Bridge

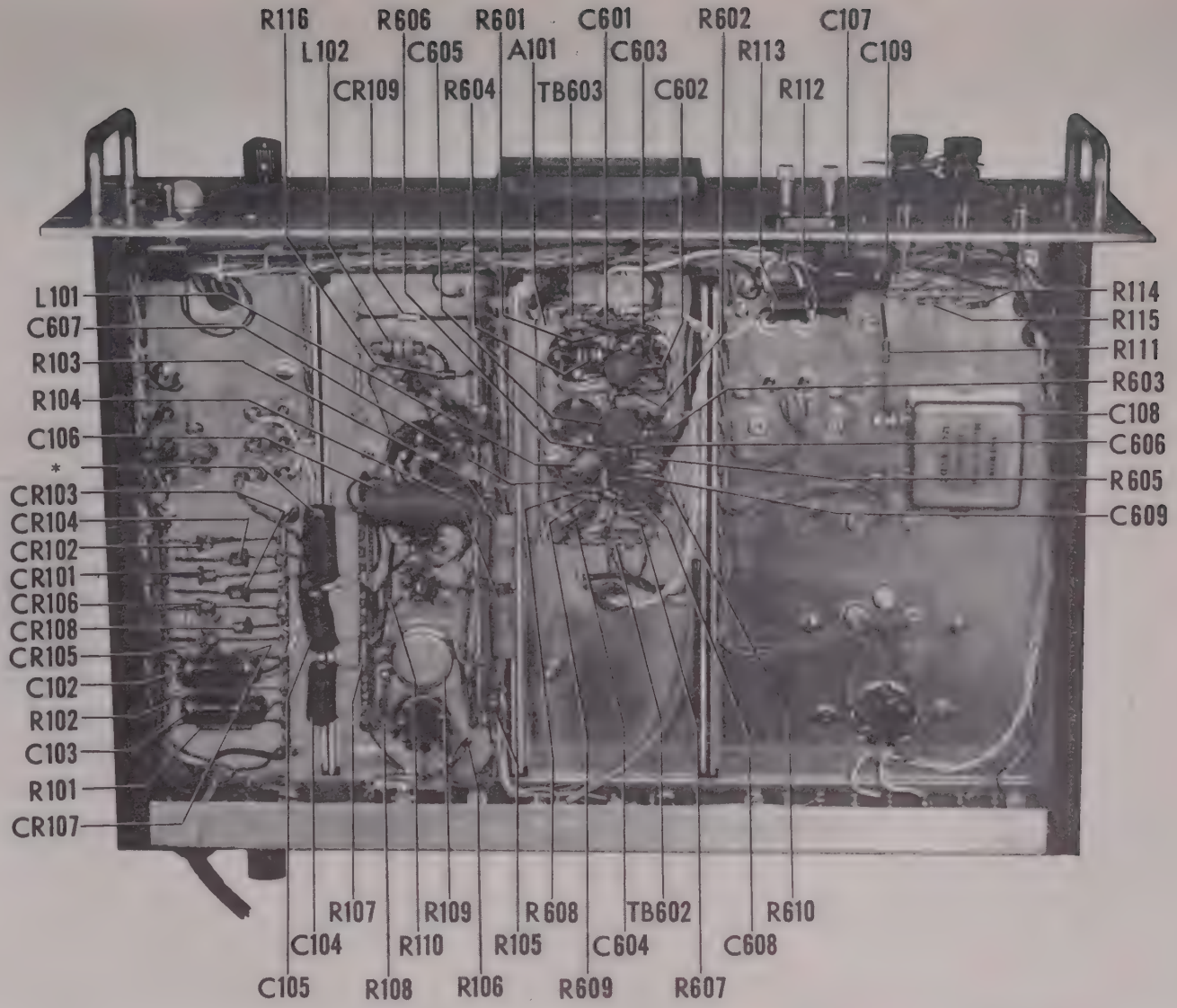


Figure 28. Bottom View of Bolometer Bridge

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
J104	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, white, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-601)	ND 60455-001	1
J105	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, black, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-603)	ND 60457-001	1
J106	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, orange, 11,000 vdc, breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-606)	ND 60459-001	1
J107	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, red, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-602)	ND 60456-001	1
J108	JACK, TIP: silver plated beryllium copper contact, integral solder terminals, molded nylon body, dark blue, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-610)	ND 60461-001	1
J109	CONNECTOR, RECEPTACLE, ELECTRICAL: 3 contact grounding, female (Harvey Hubbel type 5256)	ND 60450-001	1
J110	TERMINAL BLOCK, 8 terminals (Curtis cat. no. FTS-8)	ND 60451-001	1
J111A, J111B	POST, BINDING: non-insulated (Millen no. 37222)	ND 60417-024	2
	INSULATOR, PLATE: used with binding posts (Millen no. 37202)	ND 60416-001	1 pr.
J112 thru J116	POST, BINDING	50049-024	5
	CAP, ELECTRICAL	106524-001	5
	BASE	39139-050	5
K101	RELAY, THERMAL: 15 sec delay on energization, 115 vac coil (Agastat no. 2112-A-5)	ND 60446-001	1
L101	REACTOR: 25H (Melco part no. X-2906)	ND 60419-001	1
L102	CHOKE, RADIO FREQUENCY: 25MH, 70 ohms (Miller cat. no. 6308)	ND 60434-001	1
M101	AMMETER: 0-30 MA bridge current (Weston Model 1331)	300464-901	1
R101	RESISTOR, FIXED, WIRE WOUND: 7,000 ohms, ± 5% 5 watts (Sprague Koolohm type 5KT)	ND 60424-001	2
R102	RESISTOR, FIXED, WIRE WOUND: Same as R101		
R103	RESISTOR, FIXED, WIRE WOUND: 40,000 ohm, ± 5%, 5 watts (Sprague Koolohm type 5KT)	ND 60435-001	2
R104	RESISTOR, FIXED, WIRE WOUND: Same as R103		

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
R105	RESISTOR, FIXED, COMPOSITION: 68,000 ohms, ± 10%, 1 watt	ND 60438-001	1
R106	RESISTOR, FIXED, COMPOSITION: 330,000 ohms, ± 10%, 1/2 watt	ND 60436-001	1
R107	RESISTOR, FIXED, COMPOSITION: 470 ohms, ± 10%, 1/2 watt	ND 60439-001	1
R108	RESISTOR, FIXED, COMPOSITION: 1.2 megohms, ± 5%, 1/2 watt	ND 60437-001	1
R109	RESISTOR, VARIABLE, LINEAR PRECISION: 100,000 ohms, ± 10%, 2 watts, locking type (Ohmite type AB style CLU1041)	ND 60431-001	1
R110	RESISTOR, FIXED, COMPOSITION: 680,000 ohms, ± 5%, 1/2 watt	ND 60440-001	1
R111	RESISTOR, FIXED, COMPOSITION: 6,800 ohms, ± 10%, 1/2 watt	ND 60447-001	1
R112	RESISTOR, FIXED, WIRE WOUND: 100 ohms, + 15%, - 0%, 1/2 watt	73056-151	1
R113	RESISTOR, FIXED, WIRE WOUND: 50 ohms, ± 1%, 1/2 watt	91207-151	1
R114	RESISTOR, FIXED, COMPOSITION: 1,000 ohms, ± 10%, 1/2 watt	ND 60441-001	2
R115	RESISTOR, FIXED, COMPOSITION: 270,000 ohms, ± 10%, 1/2 watt	ND 60448-001	1
R116	RESISTOR, FIXED, COMPOSITION: Same as R114		
S101	SWITCH, TOGGLE: SPDT, 6 amp, 125 v	112452-001	1
S102	SWITCH, ROTARY: 4 pole, 2 position (Shallcross part no. 2J68A2-1)	ND 60413-001	1
T101	TRANSFORMER, POWER, STEP-DOWN AND STEP-UP: 300v-200v-6.3v (C.T.)-6.3v (Melco part no. X-2907)	ND 60418-001	1
T102	TRANSFORMER, POWER, ISOLATION: 1:1 turns ratio (Melco part no. X-2871)	ND 60420-001	1
T103	TRANSFORMER, DAMPING FEEDBACK: (Melco part no. X-2872)	ND 60421-001	1
V101	ELECTRON TUBE: Type 6CK4	ND 60427-001	1
V102	ELECTRON TUBE: Type 5654 or Type 6AK5	ND 60429-001	1
V103	ELECTRON TUBE: Type OA2	ND 60428-001	1
V104	ELECTRON TUBE: Type 6005 or Type 6AQ5A	ND 38576-001	1
W101	CABLE ASSEMBLY, POWER, ELECTRICAL: (Belden trade no. 17408-S)	ND 37821-001	1
W102	CABLE ASSEMBLY, SPECIAL PURPOSE, ELECTRICAL	300448-901	1
Z101	STANDARD RESISTANCE NETWORK: 100-100-200-200 ohms	300425-901	1

MODEL 1494-1 REFERENCE CURRENT GENERATOR
(See figures 11, 12, 29 and 30.)

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
A101	AMPLIFIER, DIRECT CURRENT: (Weston Model 9950 type 28)	186610-901	1
A102	SHUNT, CURRENT SETTING:	No Number	1
A103	Δ I MULTIPLIER CIRCUIT	No Number	1
C101A, C101B	CAPACITOR, FIXED, ELECTROLYTIC: 20-20 UF, 450 vdcw (Cornell Dubilier cat. no. UPB-14)	ND 60430-001	1
C102	CAPACITOR, FIXED, PAPER DIELECTRIC: 0.25 UF, ± 10%, 400 vdcw (Arco-Elmenco part no. 4DP-5-254)	ND 60425-001	2
C103	CAPACITOR, FIXED, PAPER DIELECTRIC: Same as C102		
C104	CAPACITOR, FIXED, PAPER DIELECTRIC: 0.1 UF, ± 10%, 600 vdcw (Arco-Elmenco part no. 6DP-4-104)	ND 60432-001	3
C105	CAPACITOR, FIXED, PAPER DIELECTRIC: Same as C104		
C106	CAPACITOR, FIXED, ELECTROLYTIC: 16 UF, 450 vdcw, (Cornell Dubilier cat. no. BR1645)	ND 60433-001	1
C107	CAPACITOR, FIXED, CERAMIC DIELECTRIC: 0.022 UF, ± 20%, 200 vdcw (Erie part no. 896-.022)	ND60445-001	1
C108	CAPACITOR, FIXED, PAPER DIELECTRIC: 16 UF, ± 20%, 150 vdcw (Astron cat. no. MD-1.5-16M)	ND 60444-001	1
C109	CAPACITOR, FIXED, PAPER DIELECTRIC: Same as C104		
CR101 thru CR108	SEMICONDUCTOR DEVICE, DIODE: Type IN 1489	ND 60422-001	8
CR109	SEMICONDUCTOR DEVICE, DIODE: Type IN 1777	ND 60423-001	1
DS101	LAMP, GLOW: neon, 0.25 watt, 115 vac (General Electric lamp no. NE-51H)	ND 60020-001	2
DS102	LAMP, GLOW: Same as DS101		
E101	CELL, MERCURY: 1.35V (Mallory cat. no. RM-42R)	ND 60476-001	1
F101	FUSE, CARTRIDGE: 2 amp (Littlefuse type 3AG)	ND 60453-001	1
G101	GALVANOMETER, INDUCTION: (Weston Model 1401 type 1)	132167	1
J101	JACK, TIP: silver plated beryllium contact, integral solder terminal, molded nylon body, brown, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-608)	ND 60462-001	1
J102	JACK, TIP: silver plated beryllium contact, integral solder terminal, molded nylon body, yellow, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-607)	ND 60460-001	1

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
J103	JACK, TIP: silver plated beryllium contact, integral solder terminal, molded nylon body, dark green, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-604)	ND 60458-001	1
J104	JACK, TIP: silver plated beryllium contact, integral solder terminal, molded nylon body, white, 11,000 vdc breakdown voltage, sigle nut mtg (E.F. Johnson cat. no. 105-601)	ND 60455-001	1
J105	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, black, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-603)	ND 60457-001	1
J106	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, orange, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-606)	ND 60459-001	1
J107	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, red, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no 105-602)	ND 60456-001	1
J108	JACK, TIP: silver plated beryllium copper contact, integral solder terminal, molded nylon body, dark blue, 11,000 vdc breakdown voltage, single nut mtg (E.F. Johnson cat. no. 105-610)	ND 60461-001	1
J110	TERMINAL BLOCK, 8 terminals (Curtis cat. no FTS-8)	ND 60451-001	1
J111 thru J115	POST, BINDING	50049-024	5
	CAP, ELECTRICAL	106524-001	5
	BASE	39139-050	5
K101	RELAY, THERMAL: 15 sec delay on energization, 115 vac coil (Agastat no. 2112-A-5)	ND 60446-001	1
L101	REACTOR: 25H (Melco part no. X-2906)	ND 60419-001	1
L102	CHOKE, RADIO FREQUENCY: 25 MH 70 ohms (Miller cat. no. 6308)	ND 60434-001	1
M101	AMMETER: 0-30 MA reference current (Weston Model 1331)	300465-901	1
M102	AMMETER: 0-100 UA difference current (Weston Model 1331)	300466-901	1
R101	RESISTOR, FIXED, WIRE WOUND: 7,000 ohms, ± 5%, 5 watts (Sprague Koolohm type 5KT)	ND 60424-001	2
R102	RESISTOR, FIXED, WIRE WOUND: Same as R101		
R103	RESISTOR, FIXED, WIRE WOUND: 40,000 ohms, ± 5%, 5 watts (Sprague Koolohm type 5KT)	ND 60435-001	2
R104	RESISTOR, FIXED, WIRE WOUND: Same as R103		

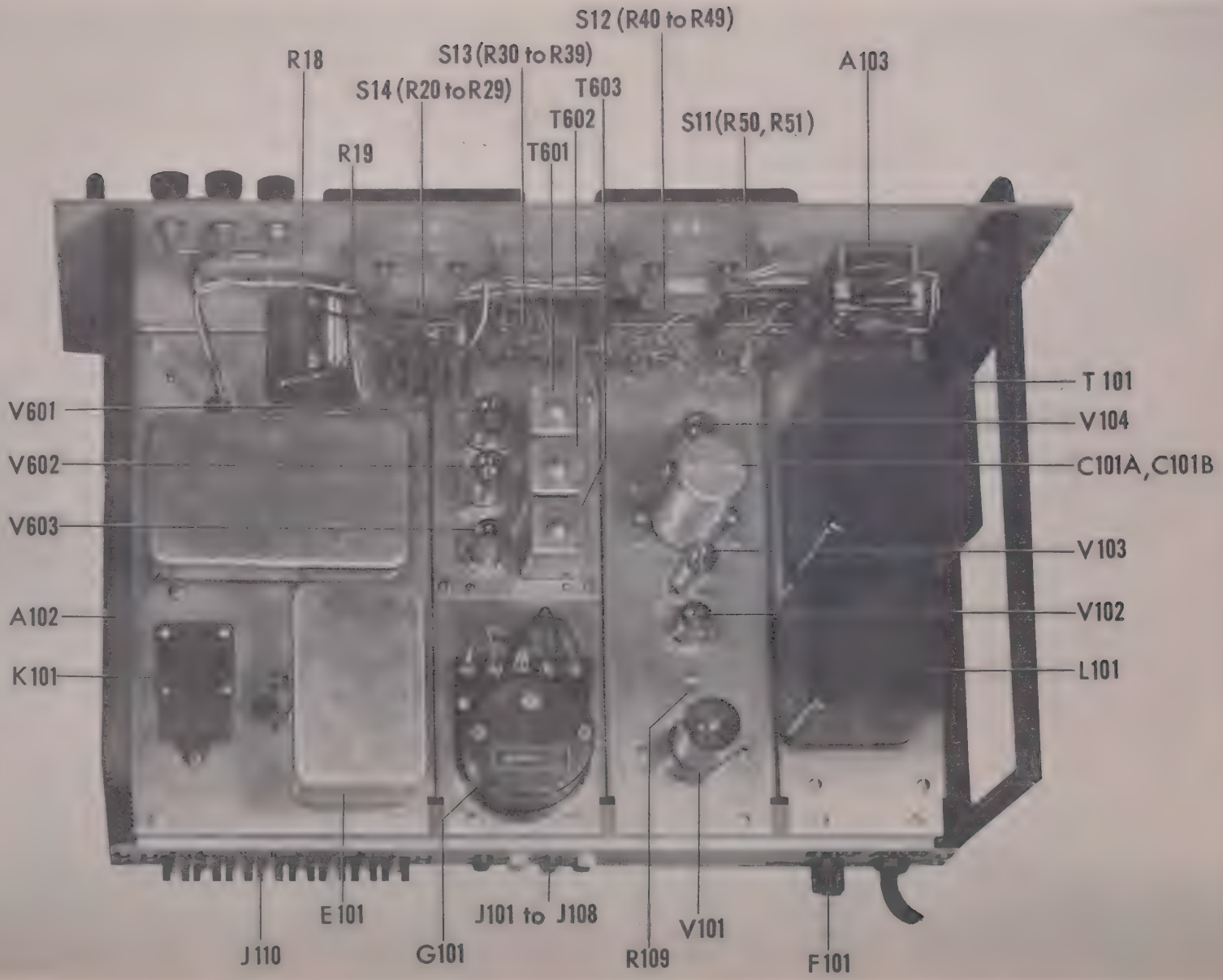
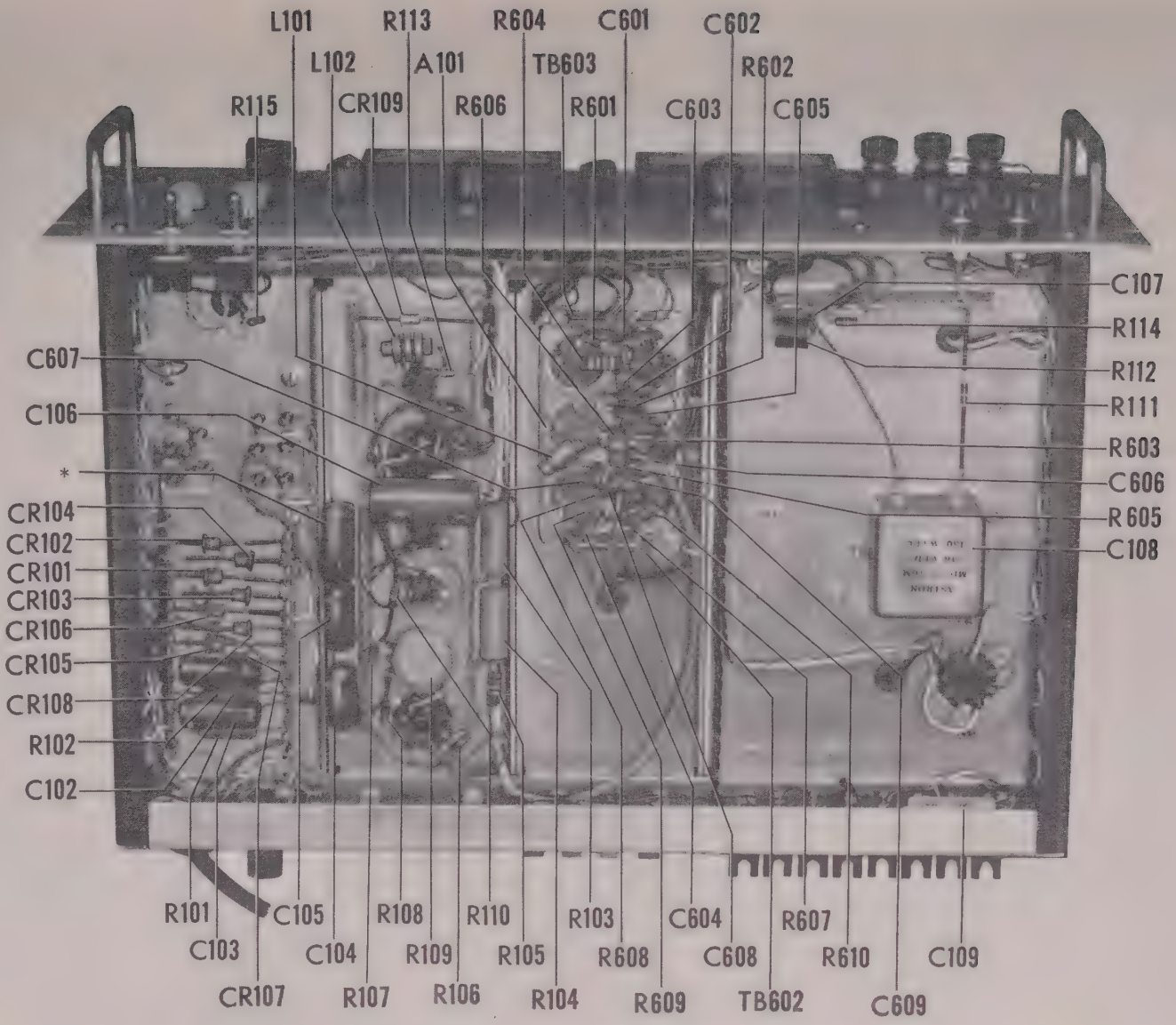


Figure 29. Top View of Reference Current Generator



*CAPACITOR - SUPPLIED IF NECESSARY

Figure 30. Bottom View of Reference Current Generator

MODEL 1494-1 REFERENCE CURRENT GENERATOR
(See figures 11, 12, 29 and 30.)

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
R105	RESISTOR, FIXED, COMPOSITION: 68,000 ohms, ± 10%, 1 watt	ND 60438-001	1
R106	RESISTOR, FIXED, COMPOSITION: 330,000 ohms, ± 10%, 1/2 watt	ND 60436-001	1
R107	RESISTOR, FIXED, COMPOSITION: 470 ohms, ± 10%, 1/2 watt	ND 60439-001	1
R108	RESISTOR, FIXED, COMPOSITION: 1.2 megohms, ± 5%, 1/2 watt	ND 60437-001	1
R109	RESISTOR, VARIABLE, LINEAR PRECISION: 100,000 ohms ± 10%, 2 watts, locking type (Ohmite type AB style CLU1041)	ND 60431-001	1
R110	RESISTOR, FIXED, COMPOSITION: 680,000 ohms, ± 5%, 1/2 watt	ND 60440-001	1
R111	RESISTOR, FIXED, COMPOSITION: 1,500 ohms, ± 10%, 1/2 watt	ND 60471-001	1
R112	RESISTOR, FIXED, WIRE WOUND: 50 ohms, ± 1%, 1/2 watt	91207-151	1
R113	RESISTOR, FIXED, COMPOSITION: 1000 ohms, ± 10%, 1/2 watt	ND 60441-001	1
R114	RESISTOR, FIXED, COMPOSITION: 220 ohms, ± 10%, 1/2 watt	ND 60470-001	1
R115	RESISTOR, FIXED, COMPOSITION: 2,700 ohms, ± 10%, 1/2 watt	ND 60469-001	1
S101	SWITCH, TOGGLE: SPDT, 6 amp, 125 v	112452-001	1
S102	SWITCH, TOGGLE: DPDT, 6 amp, 125 v	112453-001	1
T101	TRANSFORMER, POWER, STEP-DOWN AND STEP-UP: 300v-200v-6.3v (CT)-6.3v (Melco part no. X-2907)	ND 60418-001	1
V101	ELECTRON TUBE: Type 6CK4	ND 60427-001	1
V102	ELECTRON TUBE: Type 5654 or Type 6AK5	ND 60429-001	1
V103	ELECTRON TUBE: Type OA2	ND 60428-001	1
V104	ELECTRON TUBE: Type 6005 or Type 6AQ5A	ND 38576-001	1
W101	CABLE ASSEMBLY, POWER, ELECTRICAL (Belden trade no. 17408-S)	ND 37821-001	1

MODEL 9950 Type 28 DIRECT CURRENT AMPLIFIER
(See figures 27, 28, 29 and 30)

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
A101	AMPLIFIER, DIRECT CURRENT: (Weston Model 9950 type 28)	186610-901	REF
C601	CAPACITOR, FIXED, CERAMIC DIELECTRIC: 0.02 UF, ± 10%, 500 vdcw, disc type (Erie cat. no. ED-.02)	ND 38653-001	3
C602	CAPACITOR, FIXED, CERAMIC DIELECTRIC: Same as C601		
C603	CAPACITOR, FIXED, MICA DIELECTRIC: 500 UUF, ± 10%, 500 vdcw (Cornell Dubilier cat. no. 5R5T5)	ND 23555-001	1
C604	CAPACITOR, FIXED, CERAMIC DIELECTRIC: 0.01 UF, ± 10%, 500 vdcw, disc type (Erie cat. no. ED-.01)	ND 24848-001	5
C605	CAPACITOR, FIXED, CERAMIC DIELECTRIC: Same as C601		
C606 thru C609	CAPACITOR, FIXED, CERAMIC DIELECTRIC: Same as C604		
G101	GALVANOMETER, INDUCTION: (Weston Model 1401 type 1)	132167	REF
L101	CHOKE, RADIO FREQUENCY: 10 MH, 70 ohms	132746-001	1
R601	RESISTOR, FIXED, COMPOSITION: 1,000 ohms, ± 10%, 1/2 watt (IRC type GBT-1/2)	ND 20128-001	2
R602	RESISTOR, FIXED, COMPOSITION: Same as R601		
R603	RESISTOR, FIXED, COMPOSITION: 470,000 ohms, ± 10%, 1/2 watt (IRC type GBT-1/2)	ND 38644-001	1
R604	RESISTOR, FIXED, COMPOSITION: 47,000 ohms, ± 10%, 1 watt (IRC type GBT-1)	ND 27727-001	1
R605	RESISTOR, FIXED, COMPOSITION: 1 megohm, ± 10%, 1/2 watt (IRC type GBT-1/2)	ND 20401-001	1
R606	RESISTOR, FIXED, COMPOSITION: 1,800 ohms, ± 10%, 2 watt (Allen Bradley type HB121)	ND 24850-001	1
R607	RESISTOR, FIXED, COMPOSITION: 1,800 ohms, ± 10%, 1/2 watt (IRC type GBT-1/2)	ND 21091-001	2
R608	RESISTOR, FIXED, COMPOSITION: 47,000 ohms, ± 10%, 1/2 watt (IRC type GBT-1/2)	ND 20594-001	2
R609	RESISTOR, FIXED, COMPOSITION: Same as R608		
R610	RESISTOR, FIXED, COMPOSITION: Same as R607		
T601	TRANSFORMER, RADIO FREQUENCY: input, 1:4 turns ratio	186614-901	1
T602	TRANSFORMER, RADIO FREQUENCY: interstage, 1:2 turns ratio	186614-902	1
T603	TRANSFORMER, DISCRIMINATOR	186614-903	1
TB602	TERMINAL BOARD: 5 terminals (Cinch-Jones code no. 2005)	ND 38585-001	2
TB603	TERMINAL BOARD: Same as TB602		

MODEL 9950 Type 28 DIRECT CURRENT AMPLIFIER
(See figures 27, 28, 29 and 30)

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
V601A, V601B	ELECTRON TUBE: Type 12AX7 or Type 5751	ND 38577-001	1
V602	ELECTRON TUBE: Type 6AQ5A or Type 6005	ND 38576-001	1
V603	ELECTRON TUBE: Type 6AL5 or Type 5726	ND 38581-001	1

CURRENT SETTING SHUNT
(See figures 11 and 29)

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
A102	SHUNT, CURRENT SETTING	No Number	REF
R18	RESISTOR, VARIABLE: 10,000 ohms, 10 turns (Beckman Helipot Series A)	ND 60110-001	1
R19	RESISTOR, FIXED, FILM: 30,000 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0030000	1
R20	RESISTOR, FIXED, FILM: 67,500 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0067500	1
R21	RESISTOR, FIXED, FILM: 22,500 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0022500	1
R22	RESISTOR, FIXED, FILM: 11,300 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0011300	1
R23	RESISTOR, FIXED, FILM: 6,700 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0006700	1
R24	RESISTOR, FIXED, FILM: 4,500 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0004500	1
R25	RESISTOR, FIXED, FILM: 3,200 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0003200	1
R26	RESISTOR, FIXED, FILM: 2,400 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0002400	1
R27	RESISTOR, FIXED, FILM: 1,900 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0001900	1
R28	RESISTOR, FIXED, FILM: 1,500 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0001500	1
R29	RESISTOR, FIXED, FILM: 13,500 ohms, ± 1%, 1/4 watt (Weston Model 9855-2)	V20-0013500	1
R30A, R30B	RESISTOR, FIXED, WIRE WOUND: 3,375 ohms, ± 1% 1/2 watt	93454-151	2

CURRENT SETTING SHUNT
(See figures 11 and 29)

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
R31	RESISTOR, FIXED, WIRE WOUND: 2,250 ohms, ± 1%, 1/2 watt	73191-151	1
R32	RESISTOR, FIXED, WIRE WOUND: 1,130 ohms, ± 1%, 1/2 watt	300492-901	1
R33	RESISTOR, FIXED, WIRE WOUND: 670 ohms, ± 1%, 1/2 watt	112493-151	1
R34	RESISTOR, FIXED, WIRE WOUND: 450 ohms, ± 1%, 1/2 watt	71725-151	1
R35	RESISTOR, FIXED, WIRE WOUND: 320 ohms, ± 1%, 1/2 watt	300490-901	1
R36	RESISTOR, FIXED, WIRE WOUND: 240 ohms, ± 1%, 1/2 watt	300489-901	1
R37	RESISTOR, FIXED, WIRE WOUND: 190 ohms, ± 1%, 1/2 watt	300488-901	1
R38	RESISTOR, FIXED, WIRE WOUND: 150 ohms, ± 1%, 1/2 watt	300487-901	1
R39	RESISTOR, FIXED, WIRE WOUND: 1,350 ohms, ± 1%, 1/2 watt	300493-901	1
R40	RESISTOR, FIXED, WIRE WOUND: 675 ohms, ± 1%, 1/2 watt	300491-901	1
R41	RESISTOR, FIXED, WIRE WOUND: 225 ohms, ± 1%, 1/2 watt	73194-151	1
R42	RESISTOR, FIXED, WIRE WOUND: 113 ohms, ± 1%, 1/2 watt	87553-151	1
R43	RESISTOR, FIXED, WIRE WOUND: 67 ohms, ± 1%, 1/2 watt	300486-901	1
R44	RESISTOR, FIXED, WIRE WOUND: 45 ohms, ± 1%, 1/2 watt	76959-151	1
R45	RESISTOR, FIXED, WIRE WOUND: 32 ohms, ± 1%, 1/2 watt	300485-901	1
R46	RESISTOR, FIXED, WIRE WOUND: 24 ohms, ± 1%, 1/2 watt	300484-901	1
R47	RESISTOR, FIXED, WIRE WOUND: 19 ohms, ± 1%, 1/2 watt	79575-151	1
R48	RESISTOR, FIXED, WIRE WOUND: 15 ohms, ± 1%, 1/2 watt	300483-901	1
R49	RESISTOR, FIXED, WIRE WOUND: 135 ohms, ± 0.5%, 1/2 watt	300435-901	1
R50	RESISTOR, FIXED, WIRE WOUND: 67.5 ohms, ± 0.5%, 1/2 watt	300434-901	2
R51	RESISTOR, FIXED, WIRE WOUND: Same as R50		
S11	SWITCH, ROTARY: single pole, 3 position (Shallcross part no. 2J00A3-1)	ND 60465-001	1
S12	SWITCH, ROTARY: single pole, 11 position (Shallcross part no. 2J00A11-1)	ND 60466-001	3
S13, S14	SWITCH, ROTARY: Same as S12		

Δ I MULTIPLIER CIRCUIT
(See figures 11 and 29)

CIRCUIT SYMBOL	DESCRIPTION	WESTON PART NO.	QTY
A103	Δ I MULTIPLIER CIRCUIT	No Number	REF
M102	AMMETER: 0-100 UA difference current (Weston Model 1331)	300466-901	REF
R10	RESISTOR, FIXED, FILM: 2,400 ohms, ± 1%, 1/2 watt (Weston Model 9852)	173991-901	1
R11	RESISTOR, FIXED, FILM: 800 ohms, ± 1%, 1/2 watt (Weston Model 9852)	V10-0000800	1
R12	RESISTOR, FIXED, FILM: 400 ohms, ± 1%, 1/2 watt (Weston Model 9852)	166260-901	1
R13	RESISTOR, FIXED, FILM: 240 ohms, ± 1%, 1/2 watt (Weston Model 9852)	V10-0000240	1
R14	RESISTOR, FIXED, FILM: 80 ohms, ± 1%, 1/2 watt (Weston Model 9852)	V10-0000080	2
R15	RESISTOR, FIXED, FILM: Same as R14		
S10A, S10B	SWITCH, ROTARY, double pole, 9 position (Shallcross part no. 2J00A9-2)	ND 60467-001	1

A Self-Balancing Direct-Current Bridge for Accurate Bolometric Power Measurements

Glenn F. Engen

Until recently, the most accurate microwave power measurements of the bolometric type have required the use of a manual d-c bridge. A self-balancing d-c bridge has been developed that preserves the inherent accuracy of the manual bridge, extends the dynamic range of operation, and greatly simplifies the operating procedure. A general description of the equipment and operating techniques is given, followed by a comprehensive survey of the sources of error accompanying the method and the accuracy achieved.

1. Introduction

A large amount of the research effort expended in the field of low level microwave power measurement in the past few years has been directed toward a determination of bolometer-mount efficiencies, or evaluation of the validity of the r-f–d-c substitution principle.[1,2,3,4] Until recently the only accessory instrument of sufficient accuracy to utilize the results of these investigations has been a manually operated d c Wheatstone bolometer bridge. The use of this device is, however, both tedious and time consuming; the dynamic range over which the desired accuracy is achieved is rather small, and the danger of barretter burnout due to a misstep on the part of the operator is ever present.

A self-balancing d-c bolometer bridge has been developed at the NBS Boulder Laboratories, which to a large measure relieves these problems, while preserving the accuracy and extending the dynamic range of operation. To date, the technique has been employed primarily with barretter-type elements, although on the basis of preliminary results, the technique should prove equally useful with thermistors.

2. Manual Bridge

One of the simplest forms of the manual bridge previously employed at the National Bureau of Standards is shown in figure 1. The r-f power [5] is given by

$$P_{rf}=\frac{r_0}{4}(i_1^2-i_2^2), \qquad (1)$$

where i_1 and i_2 are the total currents required to balance the bridge without and with r-f power present, respectively. A precision potentiometer-standard resistor combination is used to measure i_1 and i_2. If it is assumed that this measurement contains a random error of ± 0.005 percent, it can be shown that for a typical bolometer operating at 200 ohms and requiring 8.5 ma of bias ($i_1=17$ ma) the error in measuring P_{rf} may be as large as 0.02, 0.3, and 3 percent at the 10, 1, and 0.1 mw levels, respectively, if all other sources of error are neglected. The small difference between i_1 and i_2 at low levels accounts for the deterioration in accuracy. A variety of alternative techniques have been proposed and employed with some degree of success, but it is not within the scope of this paper to examine the manual technique in detail or to establish the maximum accuracy obtainable. In practice, this is often determined by the stability requirements imposed on the generator and measuring system by the time-consuming nature of the technique, rather than by more fundamental limitations.

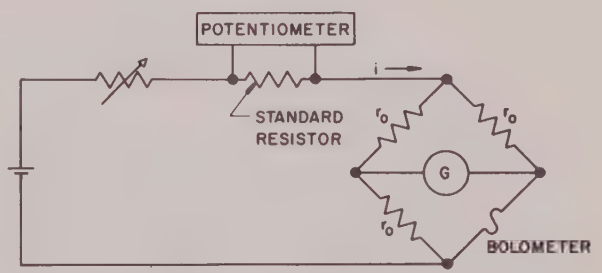


FIGURE 1. *Manual direct-current bolometer bridge.*

3. Self-Balancing Bridge

The self-balancing d-c bolometer bridge employs a d-c amplifier in a feedback loop to balance the bolometer bridge. The amplifier is connected in such a manner that the bridge unbalance signal is amplified to provide the bridge current (fig. 2). The use of this self-balancing circuit eliminates many of the time-consuming features of the technique, but the power-measurement problem is essentially the same. This problem, at low power levels, is basically one of trying to accurately measure a small change in a comparatively large d-c power.

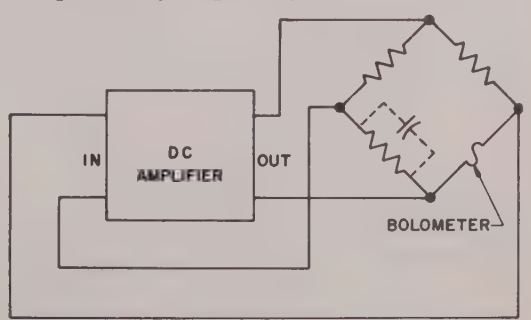


FIGURE 2. *Basic circuit of self-balancing bridge.*

[1] R. W. Beatty and Frank Reggia, An improved method of measuring efficiencies of ultra-high-frequency and microwave bolometer mounts, J. Research NBS **54**, 321 (1955) RP2594.
[2] A. C. Macpherson and D. M. Kerns, A microwave microcalorimeter, Rev. Sci. Instr. **26**, 27 (1955).
[3] H. J. Carlin and Max Sucher, Accuracy of bolometric power measurements, Proc. Inst. Radio Engrs. **40**, 1042 (Sept. 1952).
[4] D. M. Kerns, Determination of efficiency of microwave bolometer mounts from impedance data, J. Research NBS **42**, 579 (1949) RP1995.
[5] More correctly, "the retracted d-c power".

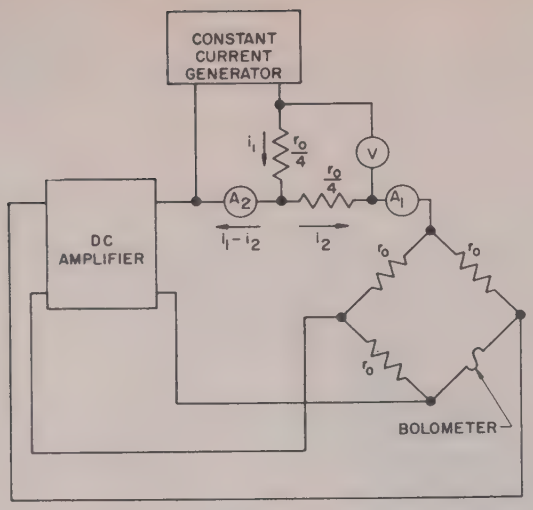


FIGURE 3. *Basic circuit for the determination of Δi and power.*

The formula for the r-f power may be rewritten

$$P_{rf}=\frac{r_0}{4}(i_1+i_2)(i_1-i_2) \tag{2}$$

$$=\frac{r_0}{4}(2i_1-\Delta i)\Delta i, \tag{3}$$

where $\Delta i=i_1-i_2$.

The difficult factor to measure accurately is Δi. A constant-current generator of high stability has been developed for use in conjunction with a differential current-measuring technique, which enables a direct and accurate determination of Δi. The circuit is illustrated in figure 3 and operates as follows: First, with no microwave power present in the bolometer, i_1 is determined by ammeter A_1, and the output of the constant-current generator is adjusted with the aid of ammeter A_2 to equal i_1 (ammeter A_2 reads zero). Then, with microwave power applied, A_2 will read Δi directly, and the power may be determined from eq (3). In practice, a potentiometer and standard resistor are employed in place of A_1 and A_2 to achieve high accuracy.

Alternatively, a voltmeter, V, connected as shown, will read $(r_0/4)(i_1+i_2)$, and the power is given by the product of V and A_2. These operations may also be combined in a single instrument of the dynamometer type to achieve a direct reading of the power.

The degree of success obtained with this technique is, of course, contingent upon the degree of stability achieved in the constant-current generator. In this case the change in generator output for a complete cutoff of bridge current is less than 1 part in 10^5, resulting in a negligible error from this source.

4. Performance

It is shown in a following section that the over-all accuracy in power measurement achieved, using a potentiometer to measure the current, is about 0.1 percent, whereas substitution of a suitable dynamometer to achieve direct reading is expected to yield an accuracy of about 0.3 percent. The instrument thus provides an increase in accuracy of 10 to 50 times that provided by the commercially avaiablel audiobridges. Other advantages over the tylpica audiobridge include: (1) Comparatively simple techniques are available for establishing, verifying, and monitoring the specified accuracy. (For example, the bridge balance may be monitored by a suitable galvanometer.) (2) The performance is, to a large degree, independent of the nominal deterioriation of the vacuum tubes and other electronic components. (3) The elimination of the audio bias power avoids its interaction with the pulse-repetition frequency in the measurement of pulse power.

At low power levels the r-f power is approximately proportional to Δi (eq 3), and the low-level performance may be displayed by recording this current with the r-f power alternately on and off. The system response to a 1-μw signal is given in figure 4.

Barring failure of the electronic components, the self-balancing operation eliminates the danger of bolometer burnout due to excessive bias current, whereas protection against an r-f overload may also be provided through use of a suitable relay to turn off the r-f source when the power input to the bolometer exceeds a prescribed amount.

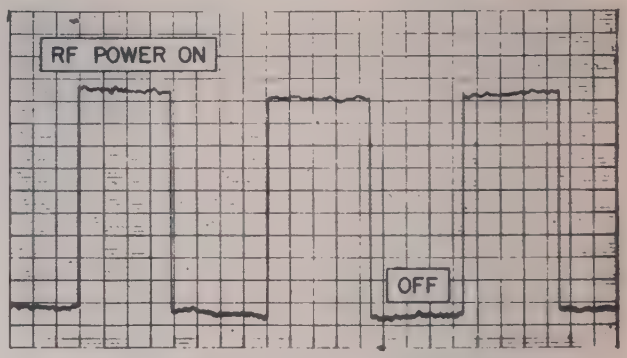


FIGURE 4. *Bridge response to a 1-microwatt signal.*
(Radiofrequency on and off for 1-minute intervals)

The d-c amplifier employed in this application is a commercially available instrument of exceptional gain, zero stability, and phase response, which was modified by the addition of a cathode follower to provide the required output current. The current amplification of the amplifier, as thus modified, is approximately 100,000. Compensation for the thermal lag of the bolometer is provided in the feedback loop by means of a condenser, as indicated in figure 2, but the achievement of stable operation with this large amplification is primarily a tribute to the amplifier phase response. The constant-current generator employs a second amplifier of the same type, which, with modification, maintains a constant-output current by reference against a mercury cell. A prototype model of this equipment is shown in figure 5

5. Analysis of Errors

The practical problems involved in making an accurate determination of the power, using eq (1) to (3), have been noted. But use of these formulas implies that the bridge is exactly balanced, the bridge arms are equal to r_0, etc. It is shown in the appendix that a more complete expression for the power is

$$P_{rf}\cong\frac{r_0}{4}(i_{b1}^2-i_{b2}^2)\left[1+Z-\frac{r_l}{r_0}+\frac{2e}{r_0(i_{b1}+i_{b2})}\left(1+\frac{8}{\gamma i_{b1}i_{b2}}\right)+\frac{16(1+g)}{\gamma i_{b2}(i_{b1}+i_{b2})}\left(\frac{1}{\alpha}-\frac{i_{s1}}{i_{b1}}\right)-\frac{2g}{(i_{b1}+i_{b2})}\left(\frac{i_{b1}}{\alpha}+i_{s2}\right)\right], \tag{4}$$

FIGURE 5. *Prototype model of self-balancing bridge, front and rear views.*

where

$\alpha=(i_{b1}-i_{b2})/(i_{g1}-i_{g2})$=current amplification of amplifier
Z=fractional deviation of the lower bridge arm from the value r_0
r_l=resistance of bolometer leads
e=thermal (or other) emf in amplifier input
i_b=total bridge current
i_g=amplifier input current
gr_0=amplifier input resistance
γ="ohms per watt" bolometer coefficient.

For a typical bolometer operating in the 0 to 10-mw region, the following values may be assigned:

$r_0=200$ ohms
$\gamma=4.5$ ohms/mw
$i_{b1}=17$ ma
$i_{b2}>8$ ma

Substituting these values in the above expression yields the result

$$P_{rf}\cong\frac{r_0}{4}(i_{b1}^2-i_{b2}^2)\left[1+Z-\frac{r_l}{r_0}+5.6e+18(1+g)\left(\frac{1}{\alpha}-\frac{i_{g1}}{i_{b1}}\right)-80g\left(\frac{i_{b1}}{\alpha}+i_{g2}\right)\right],$$

where the last three terms in the bracket reflect the inability of the d-c amplifier to balance the bridge exactly.

The characteristics of the d-c amplifier employed in this application are such that the following values obtain:

$g=1/4$ (amplifier input resistance 50 ohms)

$\alpha>10^5$ (current amplification)

$0<i_{g1}/i_{b1}<2\times10^{-5}$
$0<i_{g2}<10^{-7}$
$|e|<10^{-}$
} (amplifier zero stability).

Substituting these values in the last three terms gives a value for their sum of about 0.0002.

The bolometer lead resistance can be measured with little effort and the correction applied, so the error from this source is negligible, whereas the value of $|Z|$ can ordinarily be held to 0.0001 or less.

Finally, it is possible to measure current by means of a precision potentiometer-standard resistor combination to an accuracy of a few parts in 10^4; thus the first factor in eq (4) may be determined by the technique discussed earlier to an accuracy of about 0.06 percent.

In summary, the total limits of error are as follows:

Deviation of bridge arms from value r_0	0.01 percent.
Failure of bridge to be exactly balanced	.02 percent.
Measurement of $i_{b1}+i_{b2}$	.03 percent.
Measurement of $i_{b1}-i_{b2}$	.03 percent.
Bolometer lead resistance	.00 percent.
Amplifier noise and instability (experimentally observed)	0.1 μw.
Total	.09 percent+0.1 μw.

6. Appendix

From figure 6 the power may be expressed in the form

$$P_{rf}=\frac{r_0}{4}(i_{b1}^2-i_{b2}^2)+f(X,Y,Z,i_g,e,r_l) \qquad (5)$$

where X, Y, and Z are the deviations of each of the bridge arms from the value r_0, i_g and e are the detector current and thermal (or other) emf, respectively, and r_l the resistance of the bolometer leads.

Assuming a knowledge of the bolometer resistance law, an exact expression for the second term could be derived, but the labor required suggests the following approximate treatment. By hypothesis, the variables $X \ldots r_l$ and $f(X \ldots r_l)$ are small, and $f(X \ldots r_l)$ may, to a good approximation, be written as the sum of the first-order corrections for each of these quantities, where the correction for each of the variables is determined with the other variables

equal to zero.

Application of this technique to the circuit in figure 6 yields the following first-order expressions for the d-c power dissipated in the bolometer, and the bolometer resistance

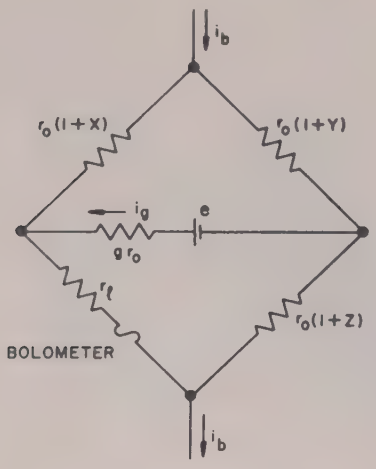


FIGURE 6. *Bridge circuit used in the evaluation of errors.*

$$P_{dc}\cong\frac{i_b^2 r_0}{4}\left[1+Z-\frac{r_l}{r_0}+\frac{2e}{r_0 i_b}-\frac{2g i_g}{i_b}\right], \tag{6}$$

$$r\cong r_0\left[1+x-y+Z-\frac{r_l}{r_0}+\frac{4e}{i_b r_o}-\frac{4(1+g)i_g}{i_b}\right]. \tag{7}$$

The failure of the expression for power to have a first-order dependence on X or Y is explained as follows: A prescribed, small value for X or Y will cause a first-order variation in bolometer resistance r, as indicated in eq (7), but also produces an unequal division of current in the two sides of the bridge. These two sources of error cancel to a first approximation. The only general requirement on the upper bridge arms is that they be equal, and if they have a nominal value of r_0, it can be shown that they may differ from each other by as much as 2 percent and produce an error in the power measurement of only 0.01 percent.

At a constant ambient temperature and assuming equivalence of d-c and r-f heating,[6] the power, P, dissipated in the bolometer will be a function of its resistance, r:

$$P=f(r).$$

Because the bolometer is nearly a square-law detector, one may in the neighborhood of an arbitrarily selected operating resistance r_0, write

$$P\cong P_0+\frac{\partial P}{\partial r}(r-r_0),$$

where P_0 is the power required to bring the bolometer to the resistance r_0 at the given ambient temperature, P is the sum of the d-c and r-f power, $P=P_{dc}+P_{rf}$, and $\partial P/\partial r$ is the reciprocial of the "ohms-per-watt" bolometer coefficient, i. e., $(\partial P/\partial r)=(1/\gamma)$. Then

$$P_{dc}+P_{rf}\cong P_0+\frac{1}{\gamma}(r-r_0).$$

P_0 may be determined by measurements in the absence of r-f power:

$$P_0\cong P_{dc}-\frac{1}{\gamma}(r_1-r_0),$$

where the subscript 1 has been used to indicate the value of quantities measured in the absence of r-f power, whereas the subscript 2 will indicate values with r-f present.

The formula for r-f power is then

$$P_{rf}=P_0-P_{dc}+\frac{1}{\gamma}(r_2-r_0)=P_{dc1}-P_{dc2}-\frac{1}{\gamma}(r_1-r_2). \tag{8}$$

In the given application, only i_g of the variables $X \ldots r_l$ has a functional dependence upon i_b, or is subject to change with the application of r-f power. Substituting eq (6) and (7) in eq (8) gives the desired result

$$P_{rf}\cong\frac{r_0}{4}(i_{b1}^2-i_{b2}^2)\left[1+Z-\frac{r_l}{r_0}+\frac{2e}{r_0(i_{b1}+i_{b2})}\left(1+\frac{8}{\gamma i_{b1}i_{b2}}\right)+\frac{16(1+g)}{\gamma i_{b2}(i_{b1}+i_{b2})}\left(\frac{1}{\alpha}-\frac{i_{g1}}{i_{b1}}\right)-\frac{2g}{(i_{b1}+i_{b2})}\left(\frac{i_{b1}}{\alpha}+i_{g2}\right)\right],$$

where

$$\alpha=\frac{i_{b1}-i_{b2}}{i_{g1}-i_{g2}}.$$

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[6] The r-f–d-c substitution error is assumed to be negligible in this discussion. For a treatment of this problem, see footnotes 2 and 3.

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Bridge a... M... Current Generator... are grounded by ... cables ... grounding is ... ground ... if the klystron power supply ... ly to ... bus, two parallel paths are provided ... current ... through the grounded bolometer load. This condition is a ... error, which can be corrected by either one of two methods

... Bolometer bridge, the chassis of the bridge and all the connected ... single lead to the panel and cabinet, and there are ... conductor in the power cable. Removing the connector ... panel will open the ground loop. Then the bridge ... through the ... the r-f conductor, and the ... the panel ... cabinet are grounded through the power ... connection will be ... to the Model 1... reference ... into the ... any other way.

... ground ... is to remove the ... on the back of the bolometer bridge ... the pin ... on the panel and cabinet ... generator ... connected to it) ... lead and grounded ... system.

... and current ... that must be connected ... to ... power supply, as would happen if the whole system ... single rack, the ground loop must be opened at two ... ground lead of the bridge should be removed as described in ... above. Also, the circuitry of the reference current generator ... its output terminals are floating with respect to the ... be accomplished by ... the Inductronic ... strip (which ... 6005 and 5726 tubes) above the chassis, ... with ... or other insulating means. If then an insulated ... connects ... '5) on this strip with the shield on the wires connected at ... strip, with terminal G on the induction galvanometer and ... except ground, which are connected by a ... in the ... the Model 1454 ... manual), the whole ... disconnected, panel ... cabinet as required. ... can be ... by means of the power cord without ... ensuring ...

Specification for Constant Current Generator-Model 1494
For use with Model 1493 Bolometer Bridge

DEFINITION: The term, "Constant Current Generator" as used in this specification is defined as an electronic device capable of providing a constant (direct) current in an external circuit, independent of changes in load resistance or electromotive forces developed within the load.

General DESCRIPTION: The constant current generator shall comprise a source of reference potential, an adjustable resistor, and a d-c amplifier connected in a self-balancing potentiometer circuit, and shall provide currents in the continuous range 3 - 30 ma with load impedances of 0 - 1000 ohms.

PERFORMANCE: Over the specified operating range, the change in output current shall not exceed five parts per million for change in the external potential, the output shall be stable to 5 parts per million for periods up to 15 minutes when operated in a laboratory environment.

NOISE: The rms noise or ripple voltage shall not exceed 0.3% of the d-c voltage across an external load resistor in the specified operating range.

CIRCUIT DETAILS: The following circuit details shall apply.

REFERENCE POTENTIAL: The source of reference potential shall be a Mallory mercury cell or equivalent. The associated circuit configuration and environment shall such as to provide optimum conditions for the stability of this cell. Suitable provision shall be made for automatically disconnecting the cell from the remainder of the circuit when the equipment is turned off.

RESISTORS: The comparison resistors employed in the potentiometer circuit shall be of the wire wound low temperature co-efficient variety, and comprise three or four decades plus a ten turn potentiometer such that a resolution in output of 1 part per million or more is provided at all current output settings.

AMPLIFIER: The d-c amplifier employed in this equipment shall be a electro-mechanical device of exceptional gain, zero stability and phase response as required to meet the overall stability required in this instrument. The d-c amplifier shall be the Weston Model 1411 Indicating Amplifier, or equivalent, followed by additional electronic amplification as required to achieve the specified output current.

GROUNDING: The circuit shall be such that one side of the external load (resistor) is at ground (chassis) potential. The direction of current flow shall be such that the ungrounded side of the load resistor is positive with respect to the ground.

PERFORMANCE SPECIFICATION

Engen Microwave Wattmeter System
(Weston Models 1493 and 1494)

System Components: A complete Engen microwave wattmeter system comprises the following component units:

1) Bolometer and bolometer mount assembly; for waveguide or coaxial terminations, as required (not supplied).

2) Bolometer Bridge, Model 1493.

3) Reference Current Supply, Model 1494.

4) Readout instrumentation, as required.

Bolometer Elements: Barretter and thermistor types (positive and negative temperature coefficients, respectively)

Bias current range; 1.5 to 15 milliamperes.

Resistance; 50, 100 and 200 ohms, with provision for external connection to reference resistors having other values.

Bridge Resolution: 0.03 percent of the full biased bolometer power.

Generated Noise: Less than the equivalent of 0.1 microwatt in the bolometer element.

Thermal Potentials: Thermal drift after 1 hour warmup, equivalent to 1 microvolt within the bolometer circuit, maximum.

Reference Resistors: NBS type, certified to 0.01 percent of the three available values, 50, 100 and 200 ohms.

Circuit Grounding: Low side of bolometer element and output current circuit brought to internal quality ground, with internal leakage shielding to avoid shunt leakage stray currents in output circuit. Leakage maximum of 0.01 microampere.

Reference Current Source: Adjustable from 3 to 30 milliamperes (equivalent to the total bridge current, or twice the bolometer current).

Short-period (5 minutes) stability, 1 part in 100,000, after 1 hour warmup.

Resolution of adjustment, 1 part in 1 million.

Internal calibration accuracy, 0.25 percent.

Load resistance range, 0-1000 ohms.

Useful Ranges: Applied to a typical 200-ohm bolometer operated at 10 milliamperes bias, approx. 0.5 ampere per watt. With a readout range of 100 microamperes this corresponds to 200 microwatts of bolometer power.

The maximum readable power corresponds to about 1/2 the total biased bolometer dissipation ($I^2 R$). In the above typical bolometer element the dissipation is 20 milliwatts, so the approximate useful maximum readable power is 10 milliwatts.

In general, the useful range of power, inclusive of the available types of bolometer elements, is about 20 microwatts to about 50 milliwatts.

The overall accuracy expectancy is 0.2 percent of the measured power, plus 2 microwatts, referred to the actual bolometer dissipation.

Output Instrumentation: The end-use application determines the required output instruments for reading and/or computing into terms of microwave power. These may be direct indicating instruments having the required order of accuracy, or a digital readout for higher accuracy, to which a digital printout may be added.

The Engen system requires a simple computation to interpret the bridge output into microwatts. This may be facilitated by a manual computer unit or performed automatically by an automatic computer unit.

The output, direct or after computation, may be applied to a servo recorder if an analog record is desired.

Following are some output instruments specifically recommended for operation with the Engen Microwave Wattmeter System:

Model 622 Laboratory Portable Milliammeter (0.25 percent).

Model 325 Laboratory Standard Milliammeter (0.1 percent).

Model 1492 ADIT Digital Milliammeter (0.02 percent).
(with optional digital printer)

Model 6702 Recording Milliammeter (0.25 percent).

Manual Computer Unit.

Automatic Computer Unit.

The most complete system combination comprises the Model 1493 Bridge and the Model 1494 Reference Current Supply, the Automatic Computer Unit, and the Model 1492 ADIT equipped with a digital printer. This system is capable of precise and fully automatic logging of microwave power within the full ability of the Engen system.

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